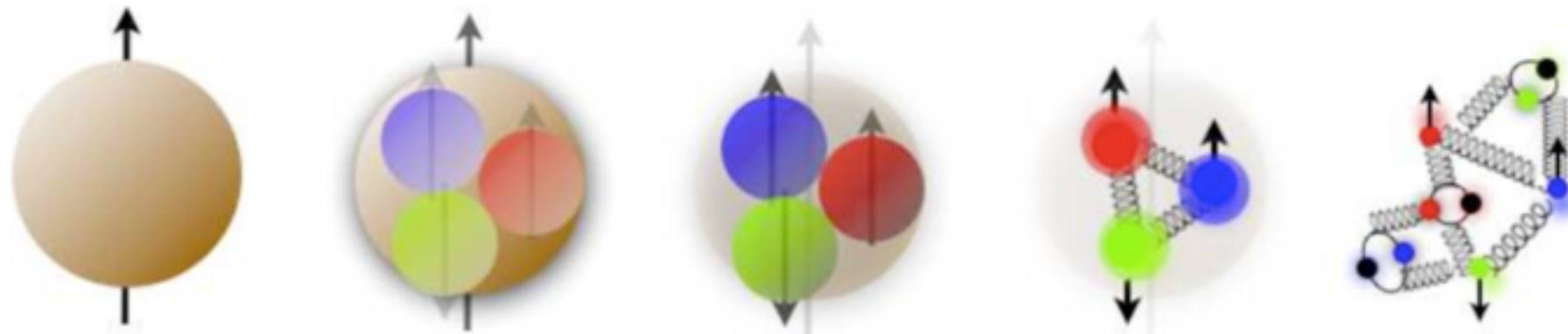


STAR ★ Cold QCD Measurements

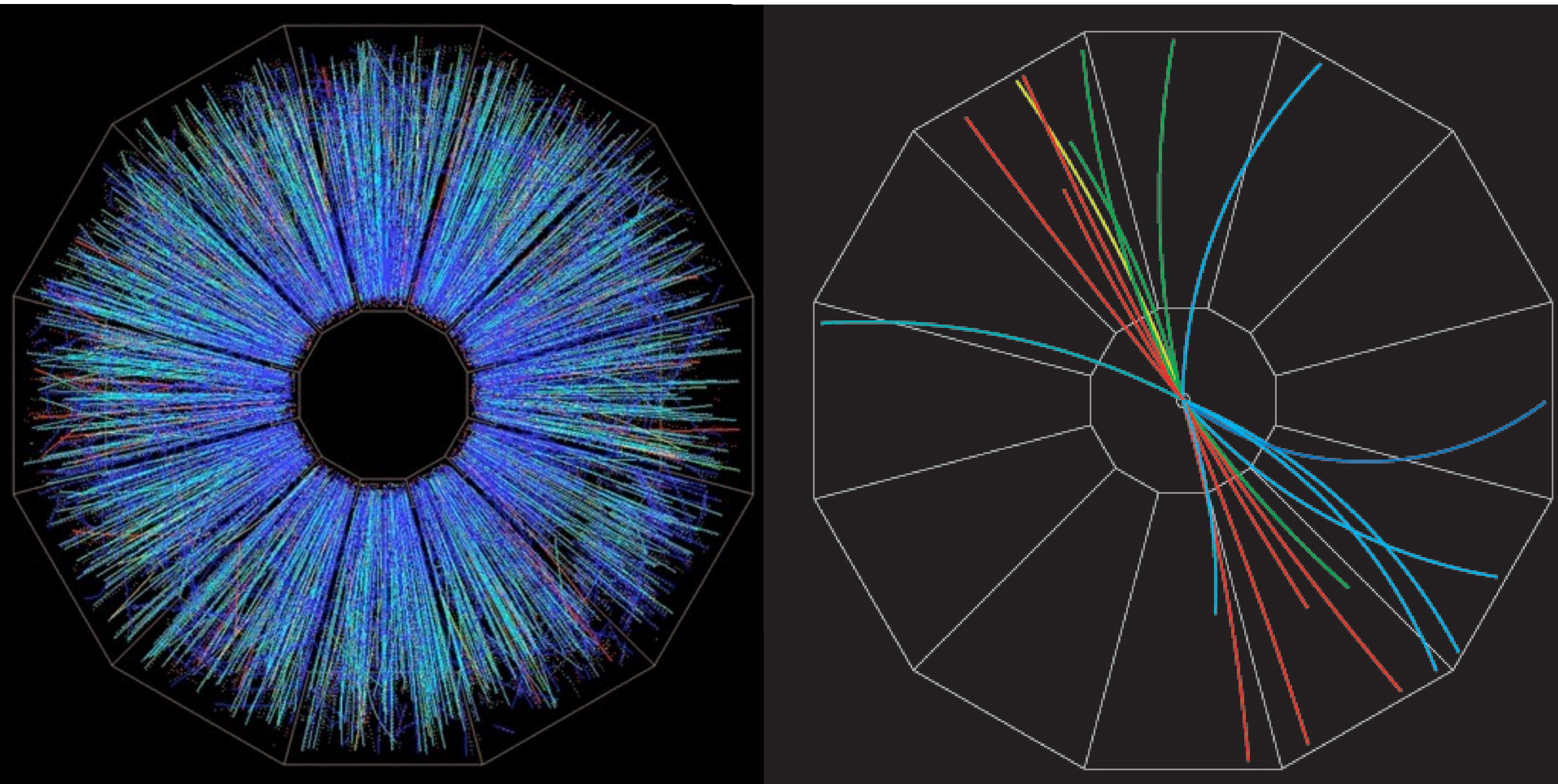
Status and Prospects



Ernst Sichtermann

Lawrence Berkeley National Laboratory

Solenoidal Tracker **At RHIC**



A versatile instrument to study QCD: A+A, p+A, p+p, $\sqrt{s} = 7.7 - 510$ GeV, polarization.

EEMC

Magnet

MTD

BEMC

TPC

TOF

BBC

Heavy Flavor Tracker

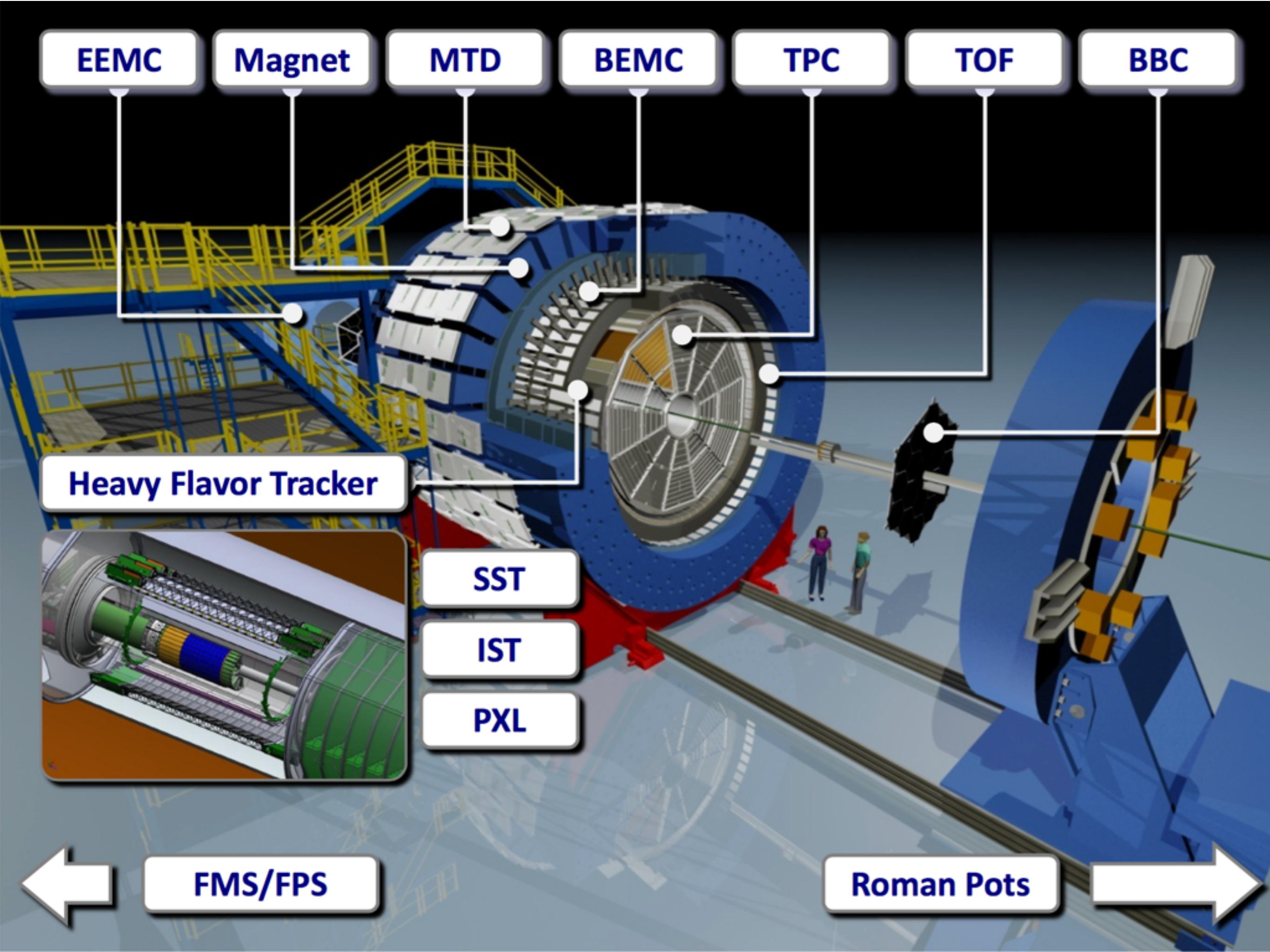
SST

IST

PXL

FMS/FPS

Roman Pots



EEMC

Magnet

MTD

BEMC

TPC

TOF

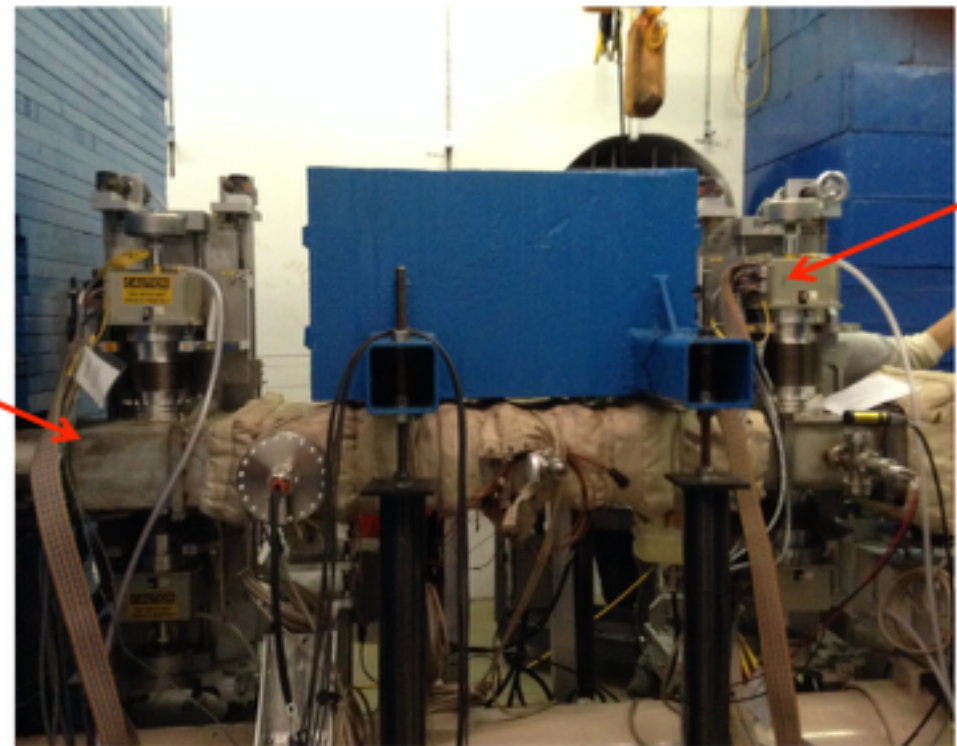
BBC

A near-perfect mid-rapidity instrument,
gaining qualitatively new fwd capabilities.



New DX-D0
Chamber

Roman Pot

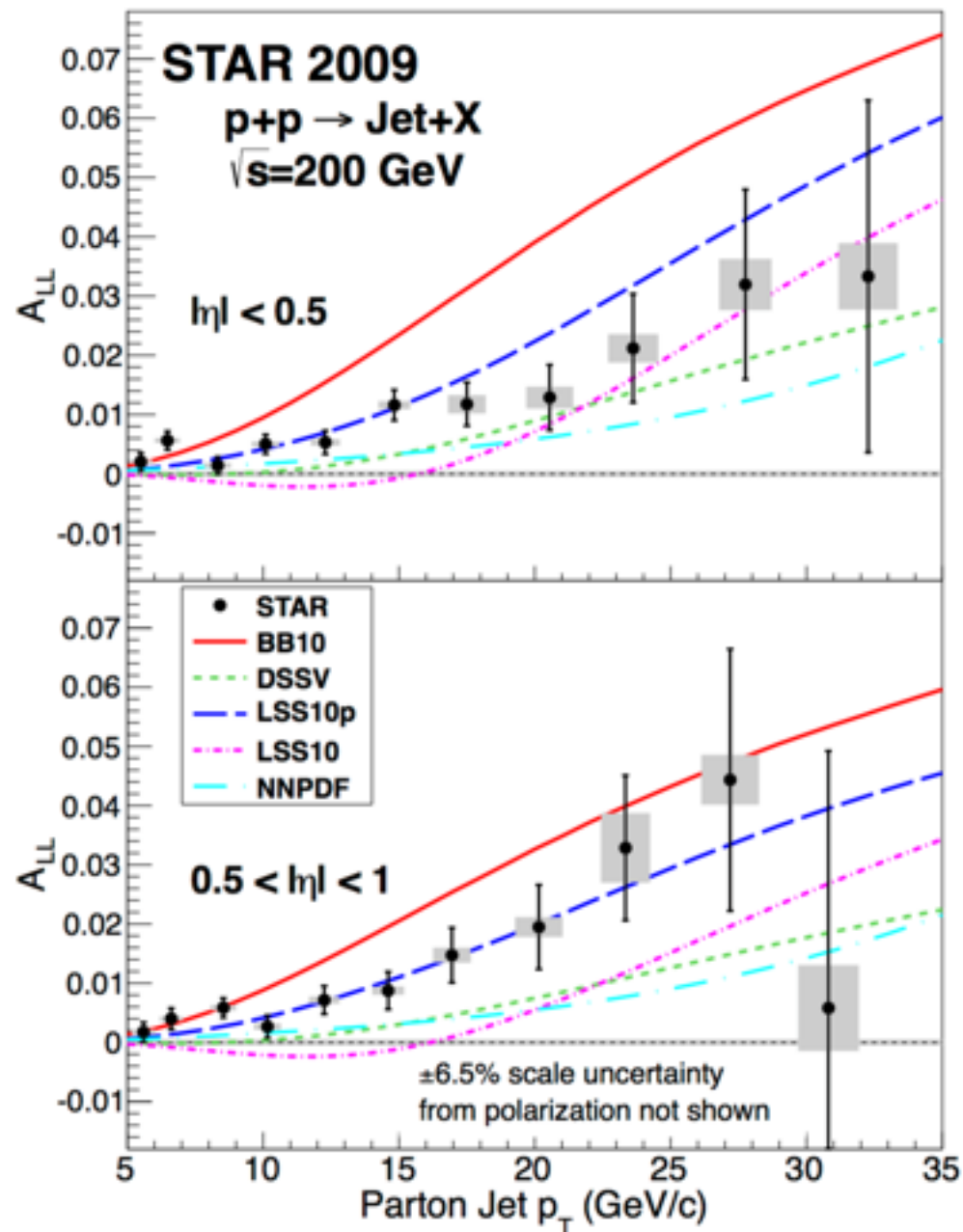


FMS/FPS

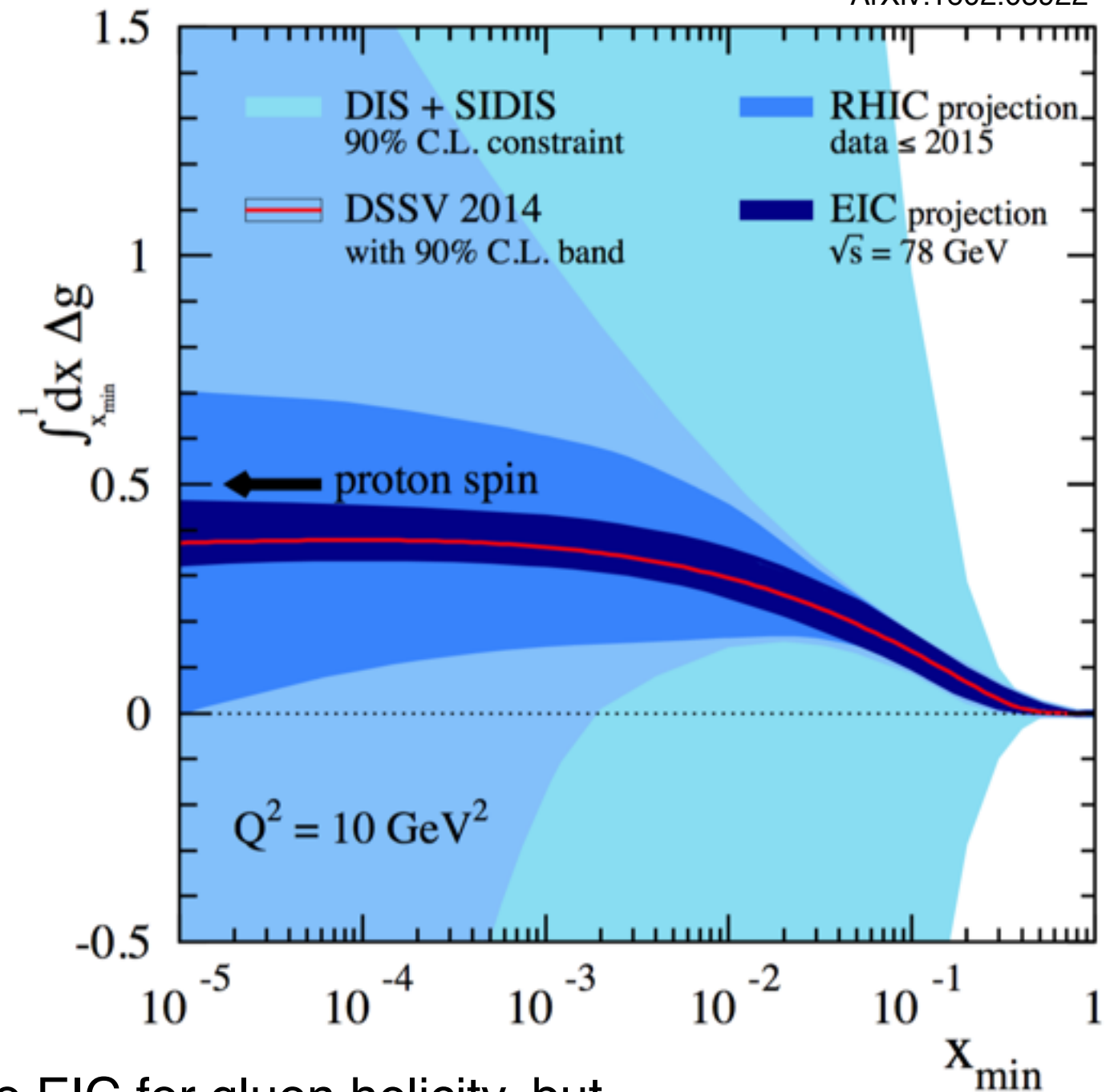
Roman Pots

STAR Jets - Gluon Polarization

PRL 115 (2015) no 9. 092002



ArXiv:1602.03922

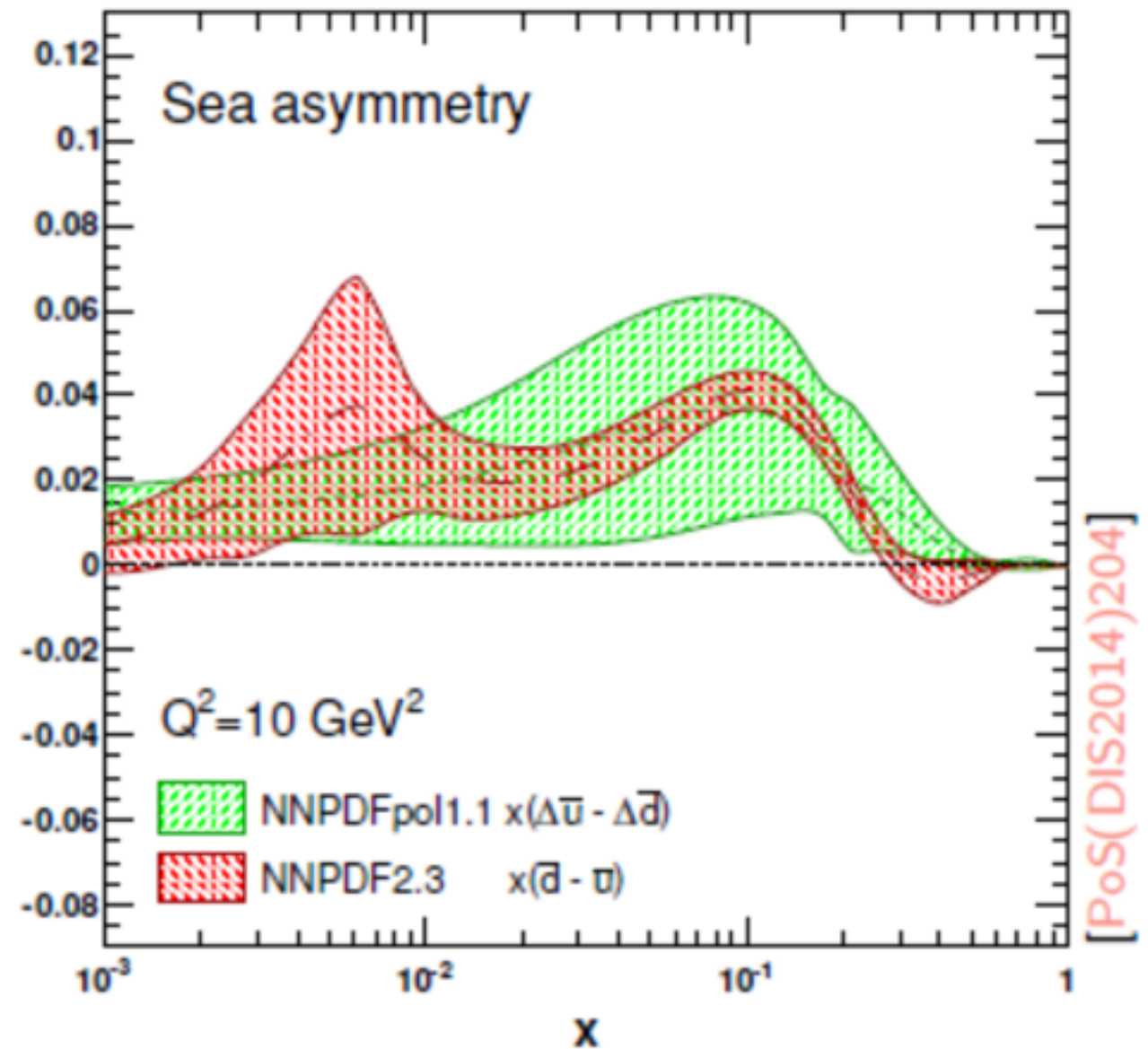
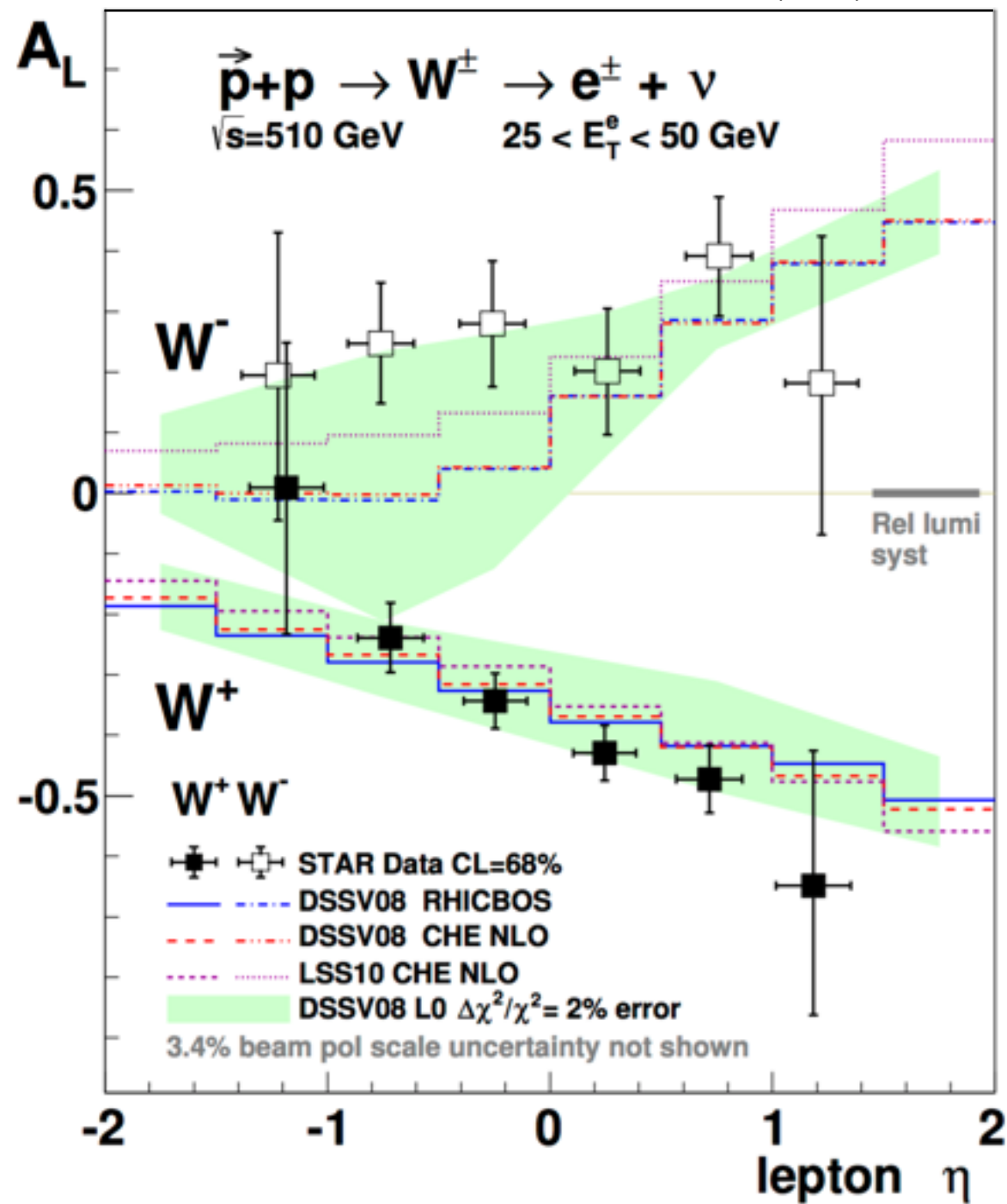


RHIC has been an essential precursor to EIC for gluon helicity, but is quite fundamentally not a substitute for EIC.

Timelines and running scenarios for > 2020 are uncertain; upgrade (plan) should include forward (di-)jet capability.

STAR W A_L - Quark Polarization

PRL 113 (2014) 072301

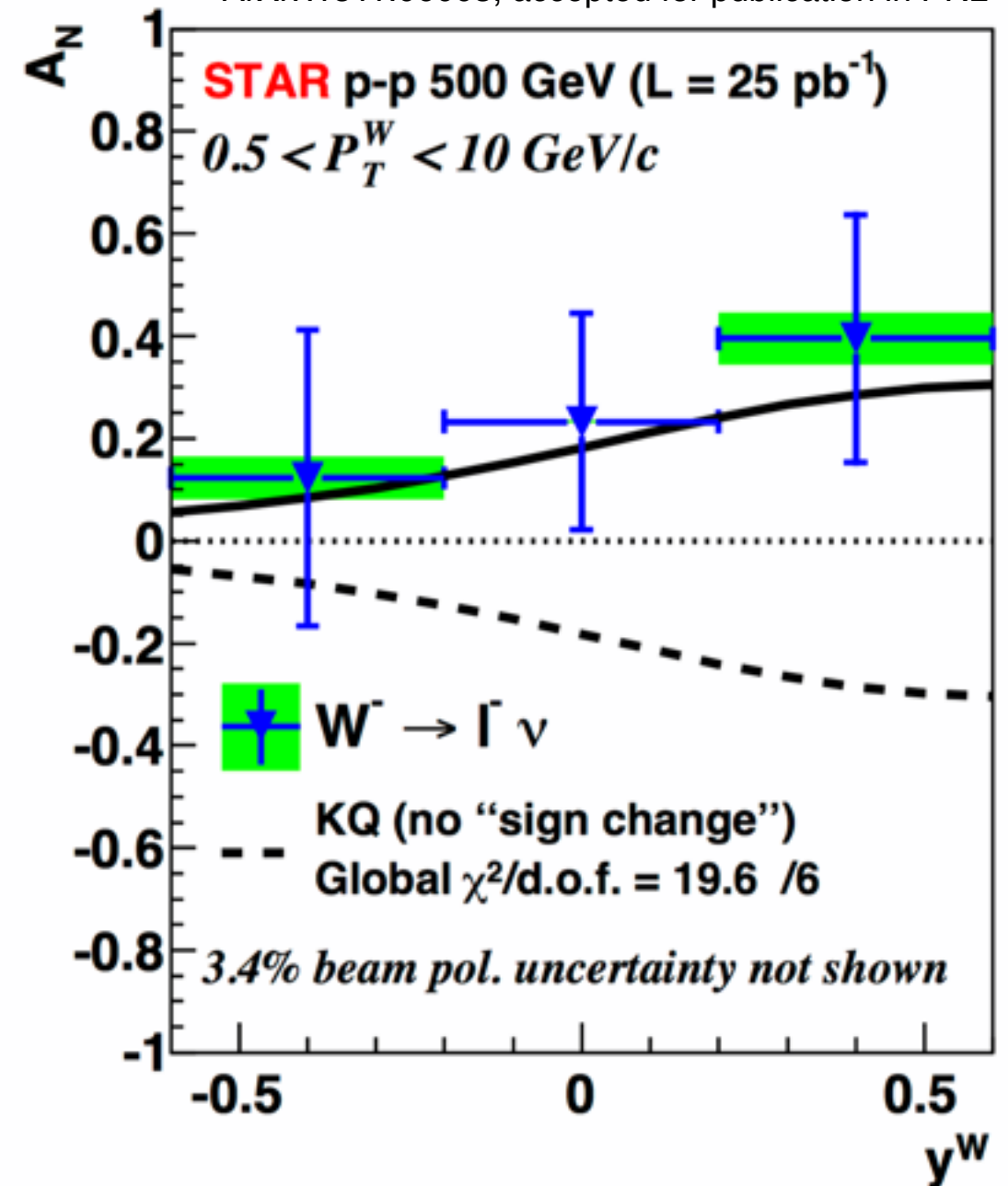
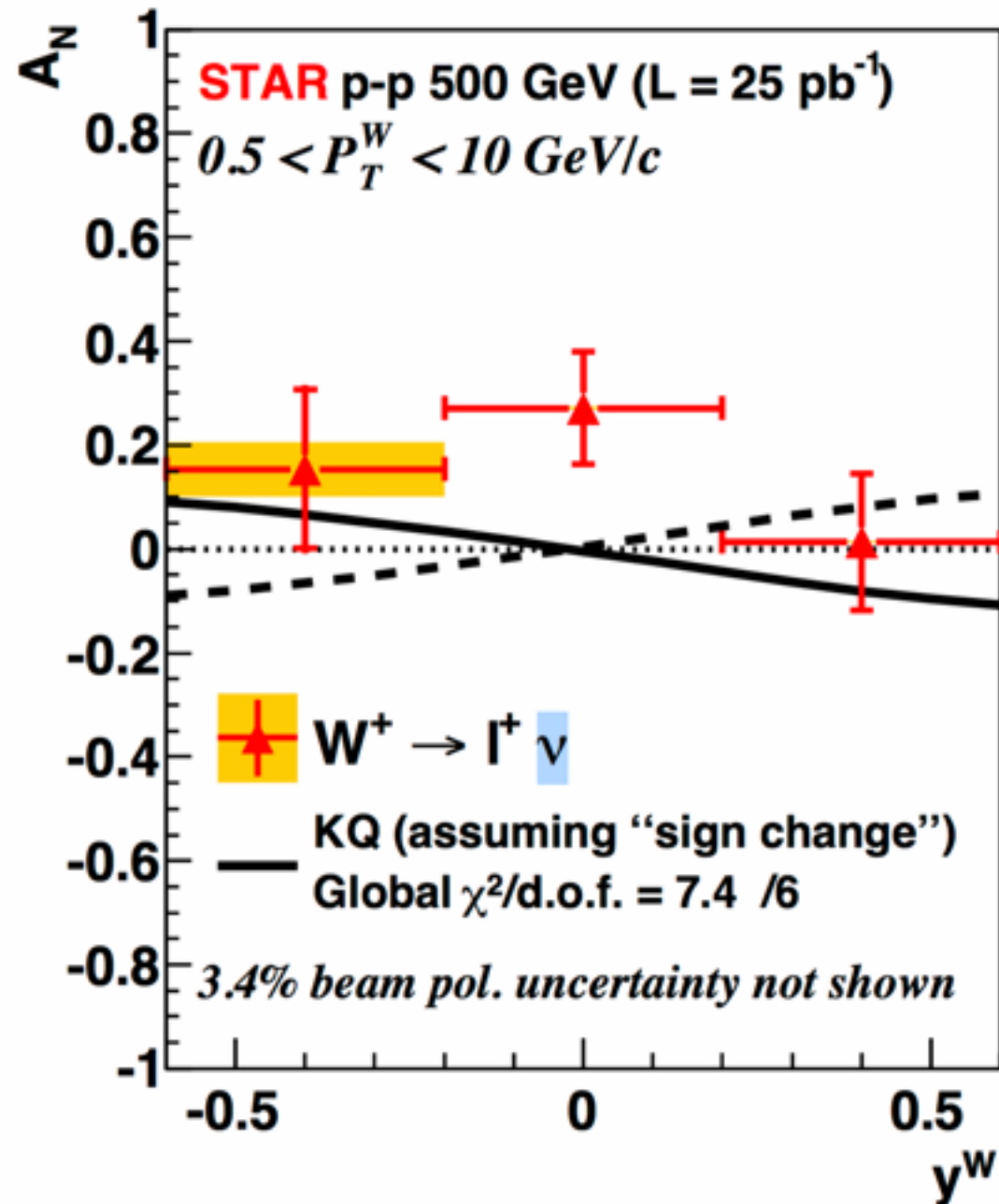


RHIC mid-rapidity W program has been successful beyond most expectations,

The light-sea has a spin structure that is non-perturbative,

STAR W A_N - “The sign change”

ArXiv:1511.06003, accepted for publication in PRL



Calls for continued measurement; the question of “sign-change” is shifting to that of “TMD evolution”,

Eagerly anticipate forward photon A_N from run-15; A_N DY has published forward jet A_N ,

Upgrade (plan) should have Drell-Yan capability,

EEMC

Magnet

MTD

BEMC

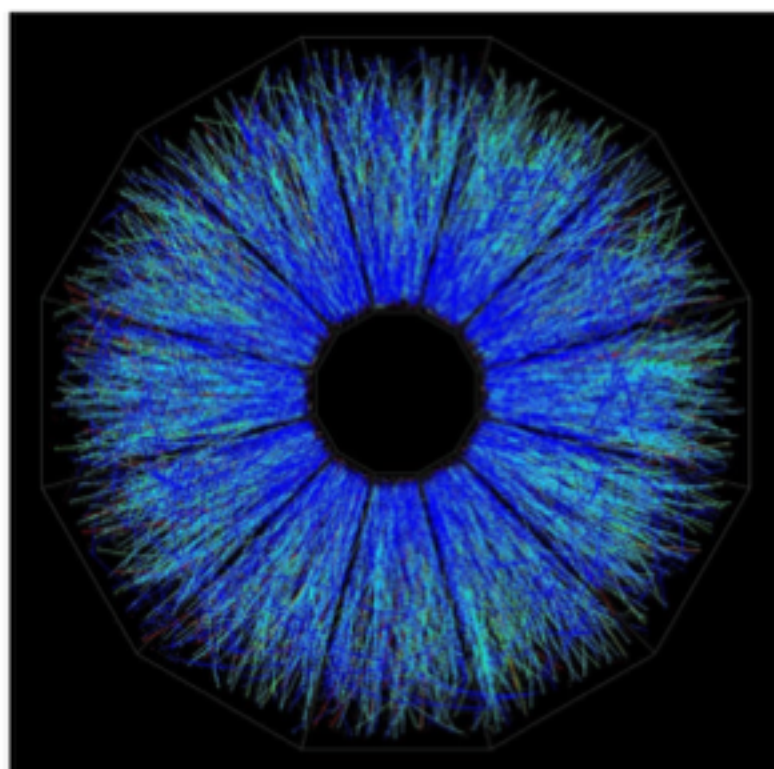
TPC

TOF

BBC

RHIC Beam Use Request For Runs 16 and 17

The STAR Collaboration



May 19, 2015

“For Run 17, the PAC endorses at least 11 weeks of transversely polarized p+p running at $\sqrt{s} = 510$ GeV”,

Endorsed also by the wider community via its LRP,

as well as BNL management.

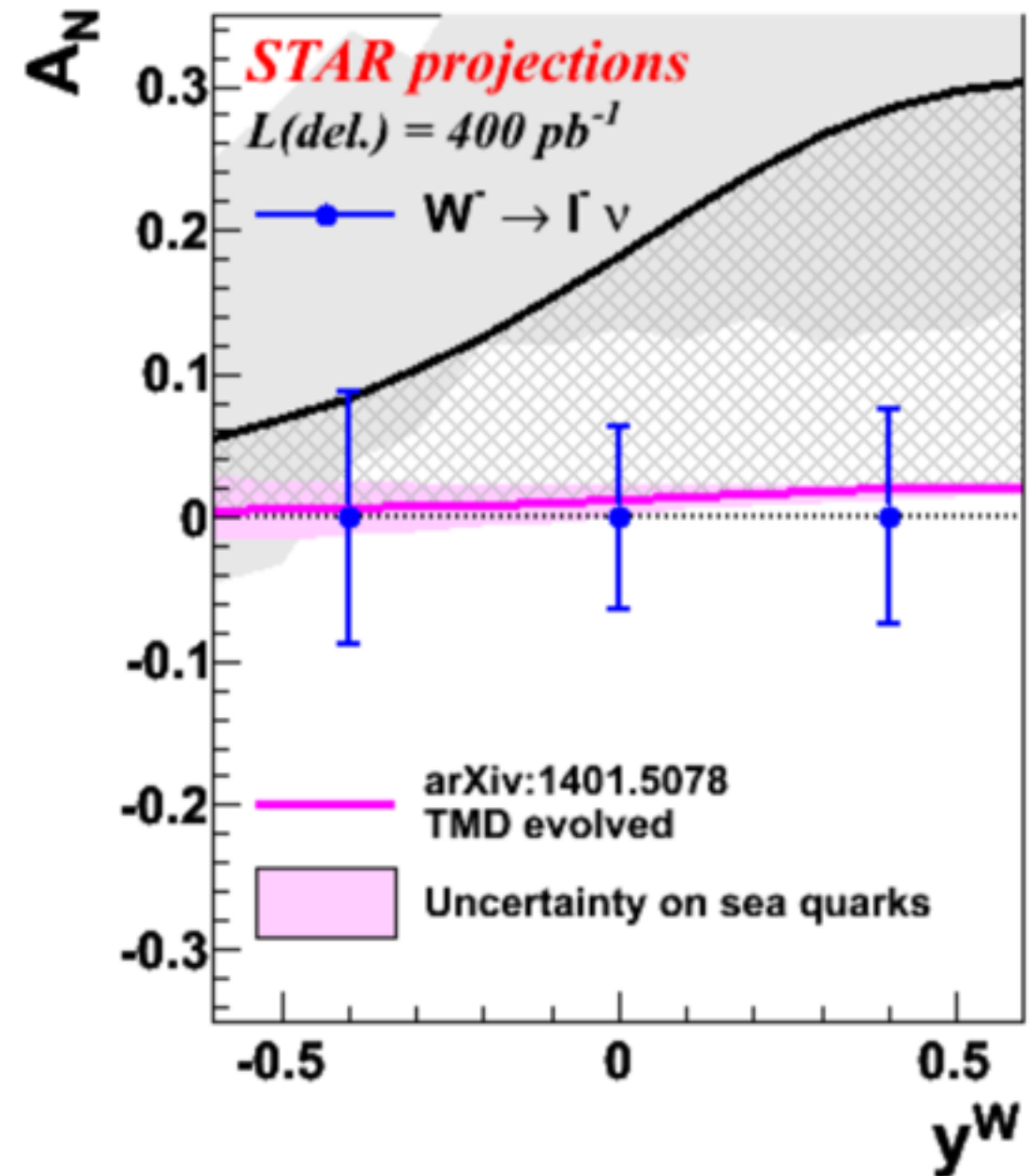
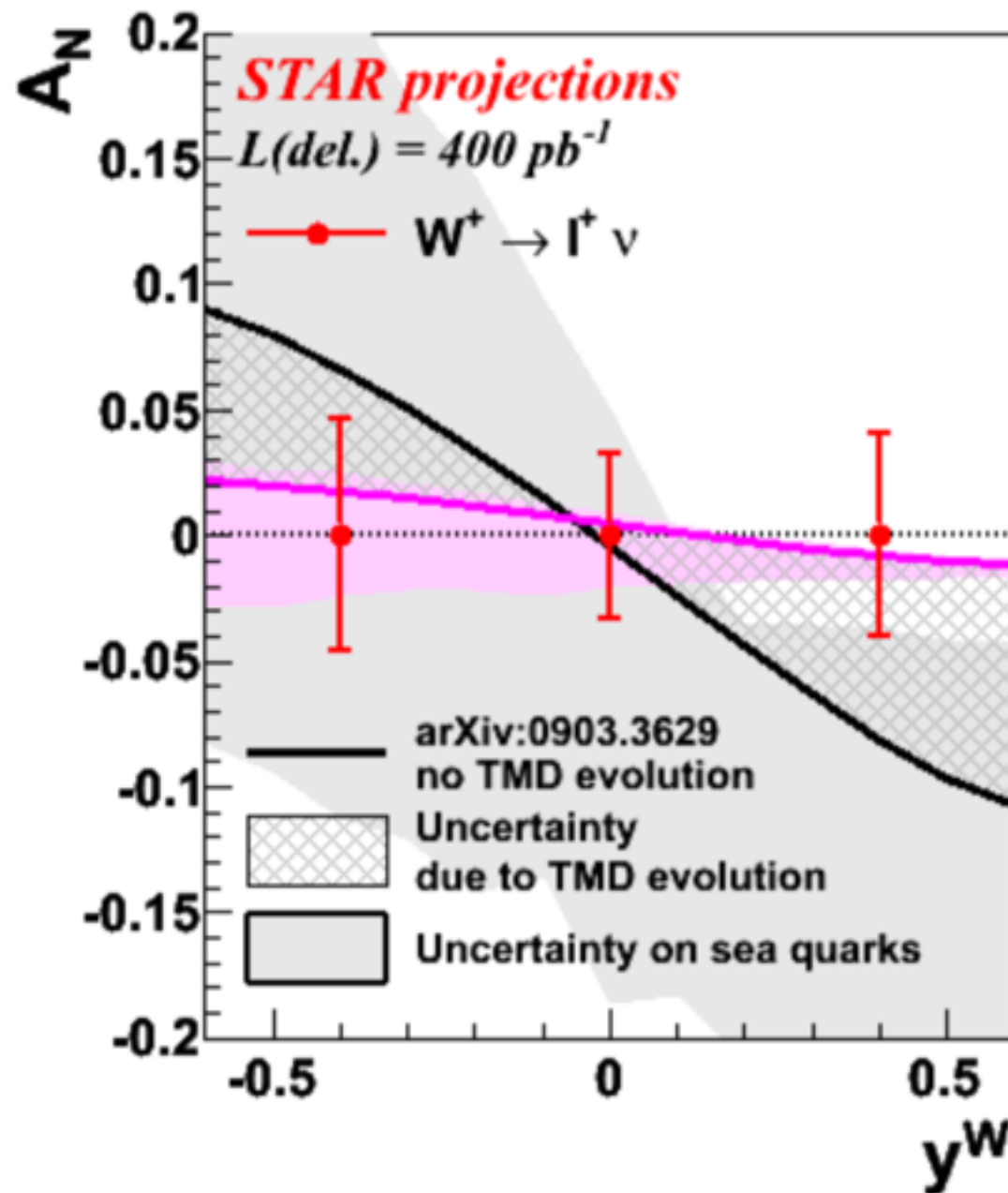
STAR welcomes new collaborators.

FMS/FPS

/ tailcatcher

Roman Pots

STAR W A_N - Prospects for Run-17



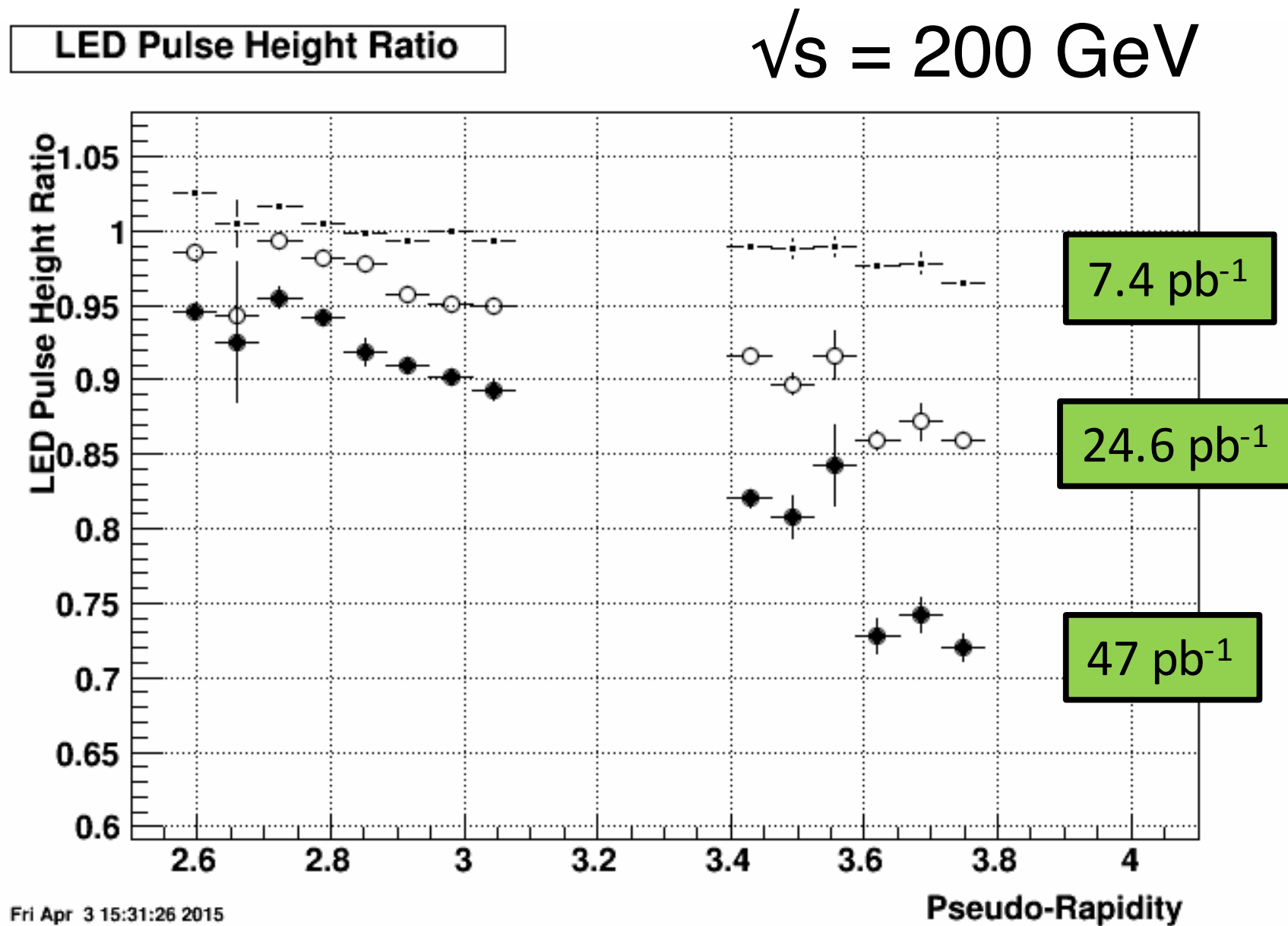
Lots of work ahead to turn these projections into actual results,

Ample other opportunities, for example

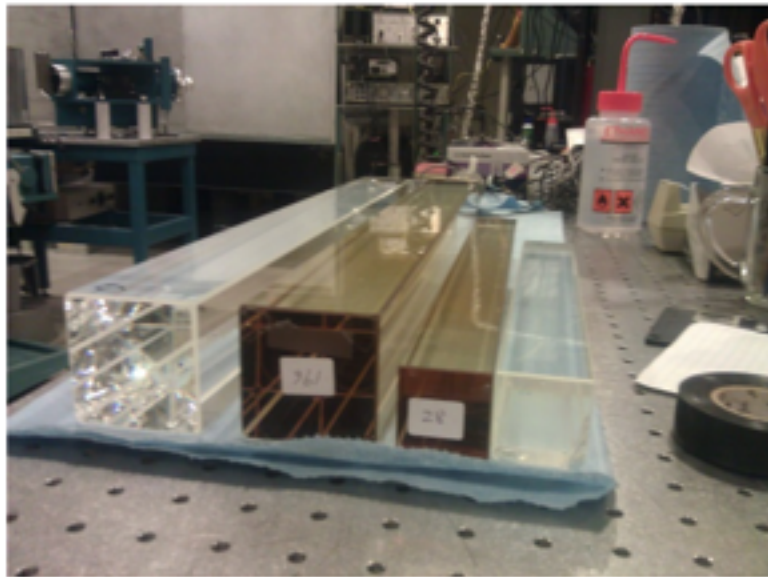
photons, Drell Yan, diffraction, mid-rapidity,

gradual upgrades to existing STAR forward instrumentation, RHICf@STAR,

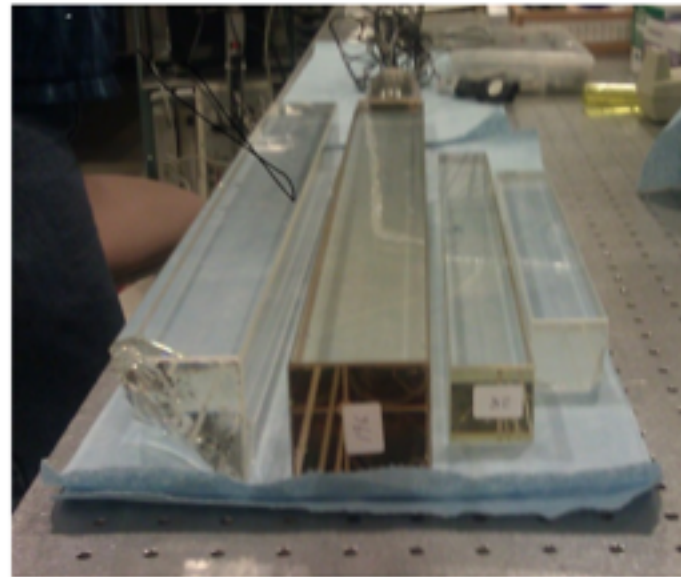
STAR FMS - (reversible) damage to PbGl



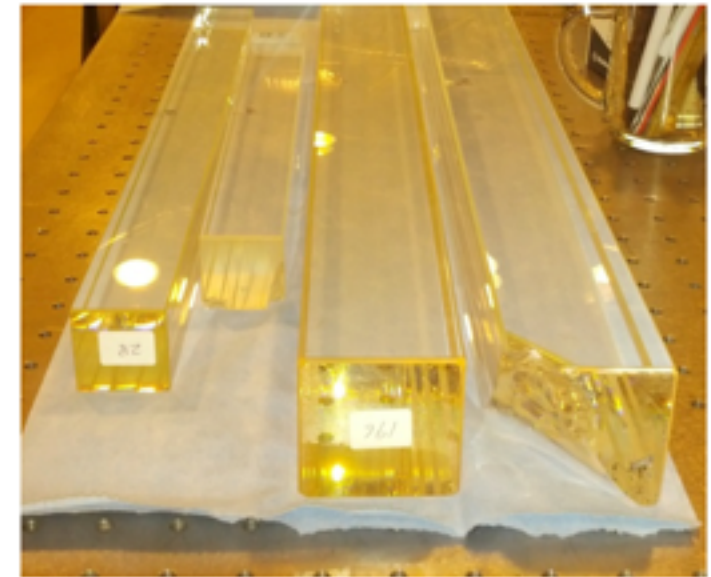
STAR FMS - reversing the PbGI damage



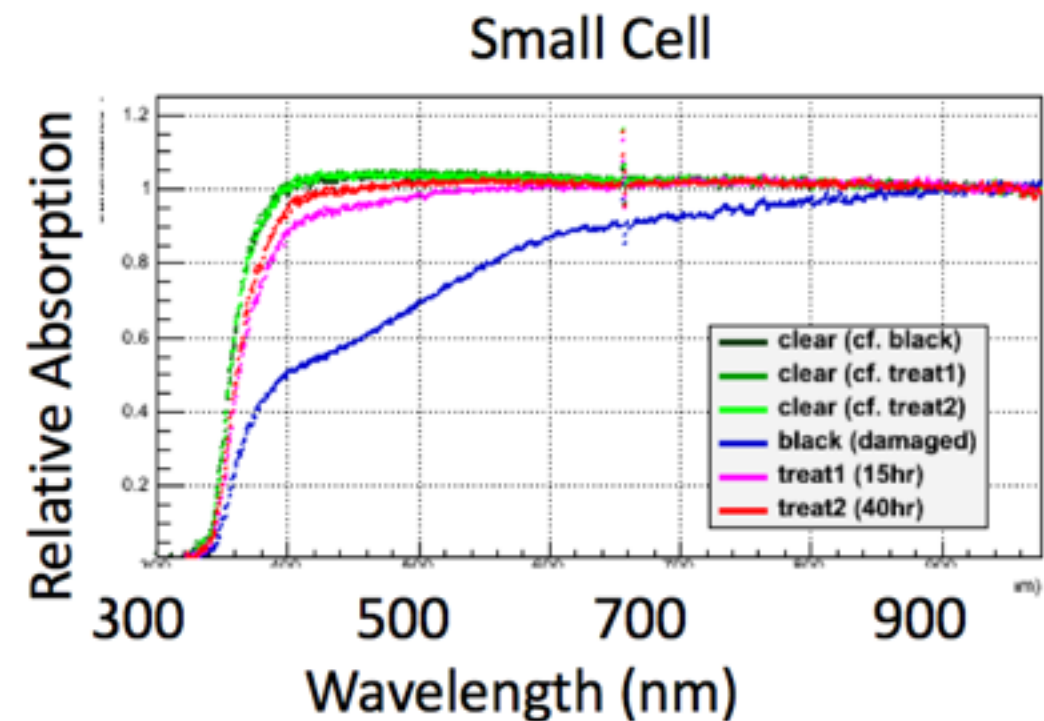
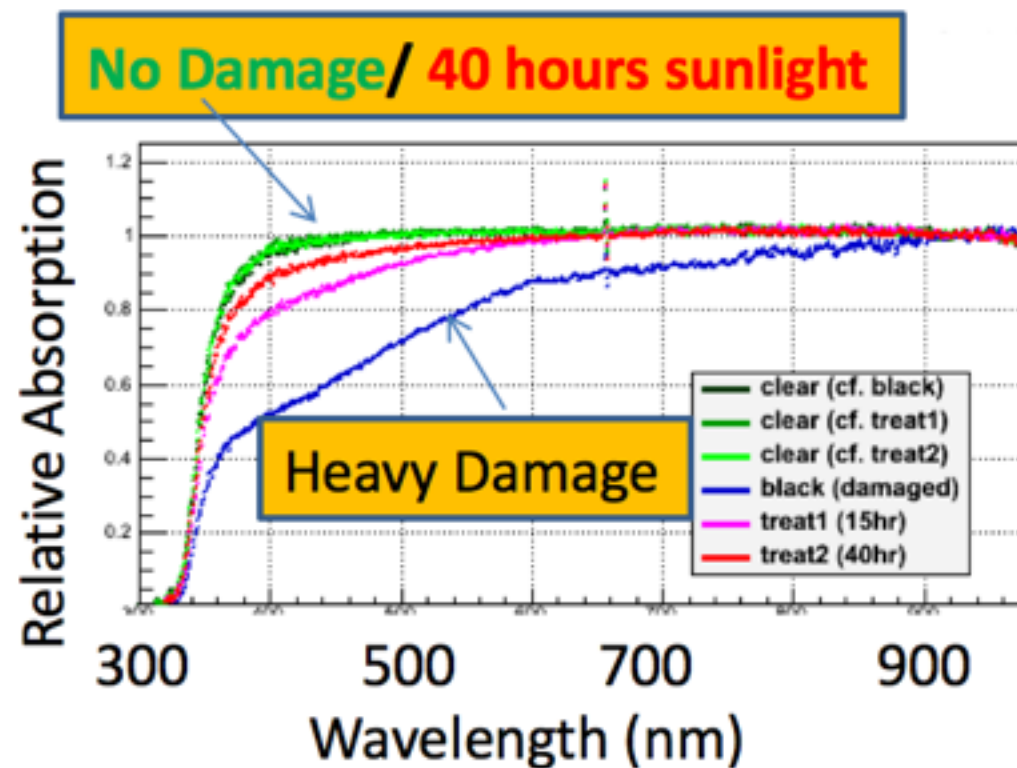
0 hours



15 hours



40 hours



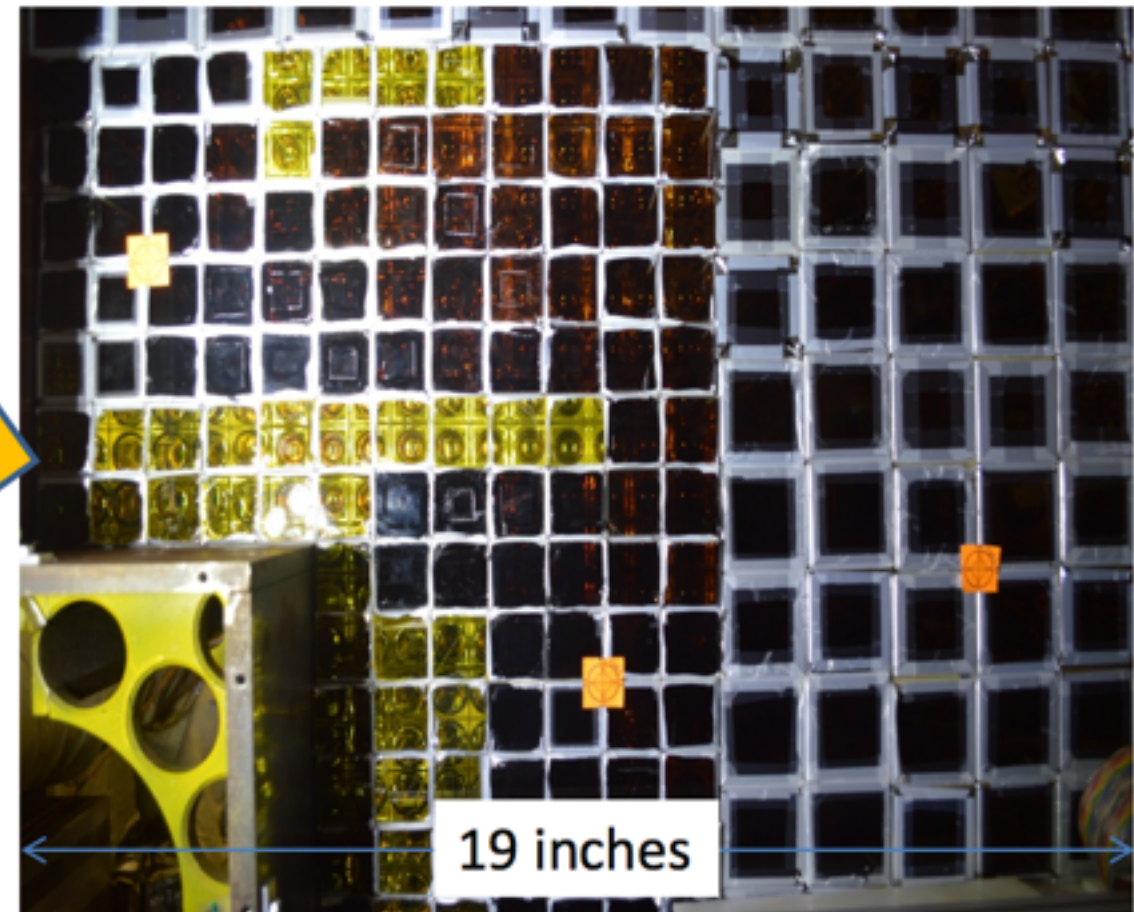
The FMS was annealed and restacked prior to Run-15, as part of other maintenance.

STAR FMS - in-situ annealing for Run-17

Off axis view of lead glass stack.
UV system must fit in this space
between the frame and glass.



Front View: Detail of lead glass darkening
Blocks are precisely square...they appear
uneven because they are wrapped in
aluminized mylar.



Clear 'radiation hard' glass appears yellow, but transparent
Damaged glass appears black in the worse areas and brown in less affected areas

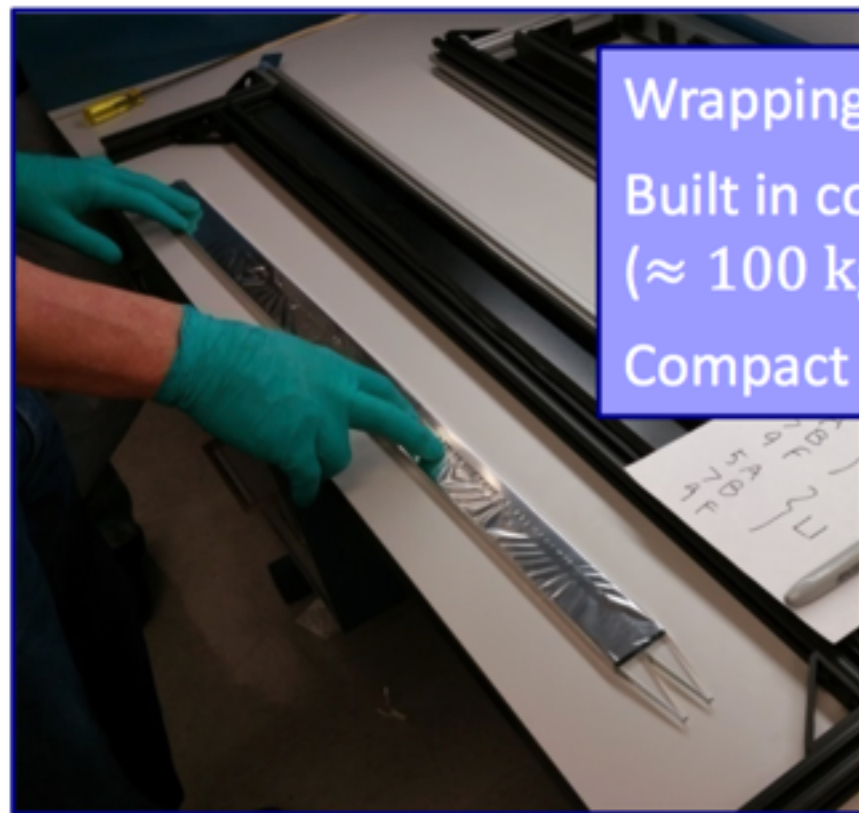
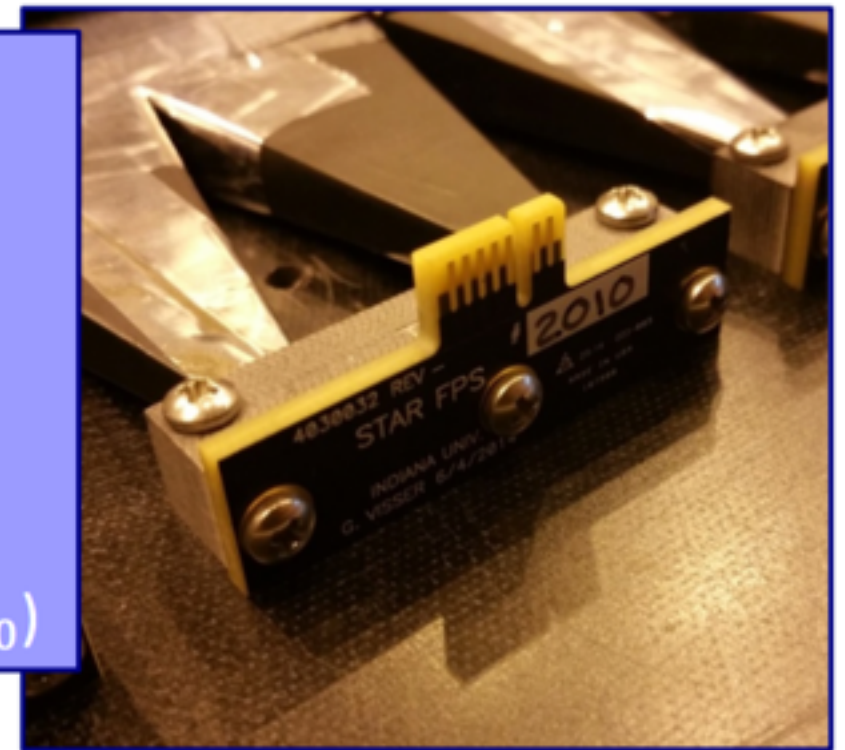
under active development.

STAR Preshower (installed before Run-15)

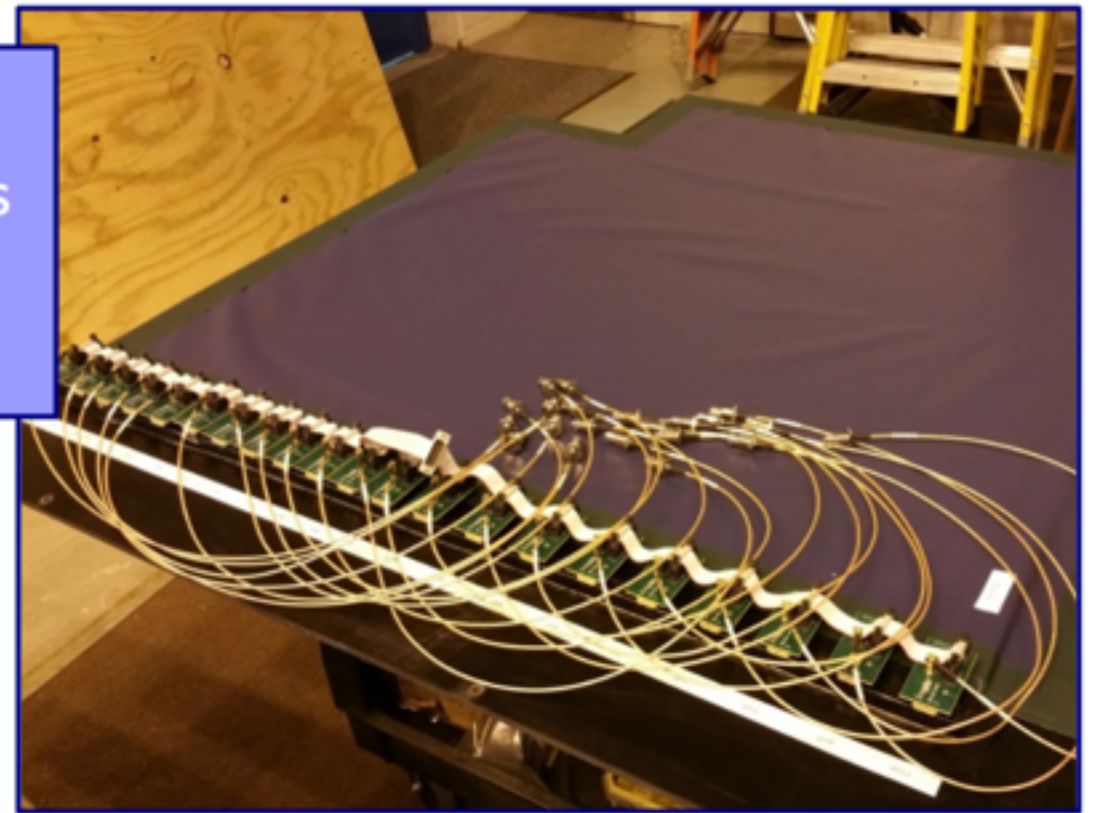


Scintillator hodoscope
4.0 / 5.8 cm wide, 1 cm thick

- Double pyramid light guide
- SiPM readout
- Three layers for 2d hit reconstruction
- 3×84 channels
- Pb converter ($d = 1 X_0$)

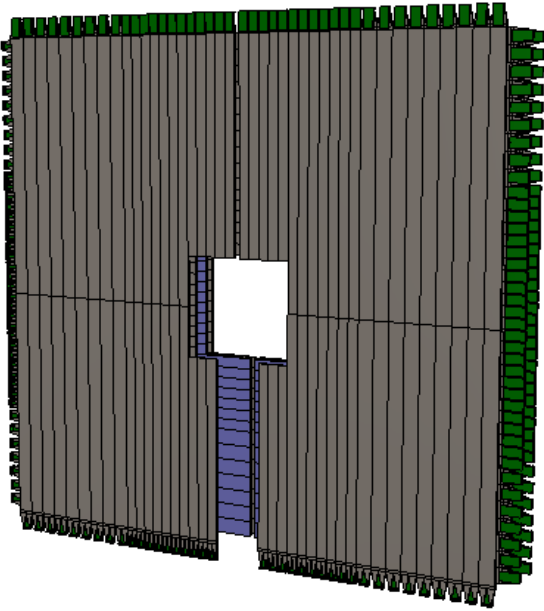


Wrapping at BNL
Built in complete quadrants
(≈ 100 kg)
Compact installation

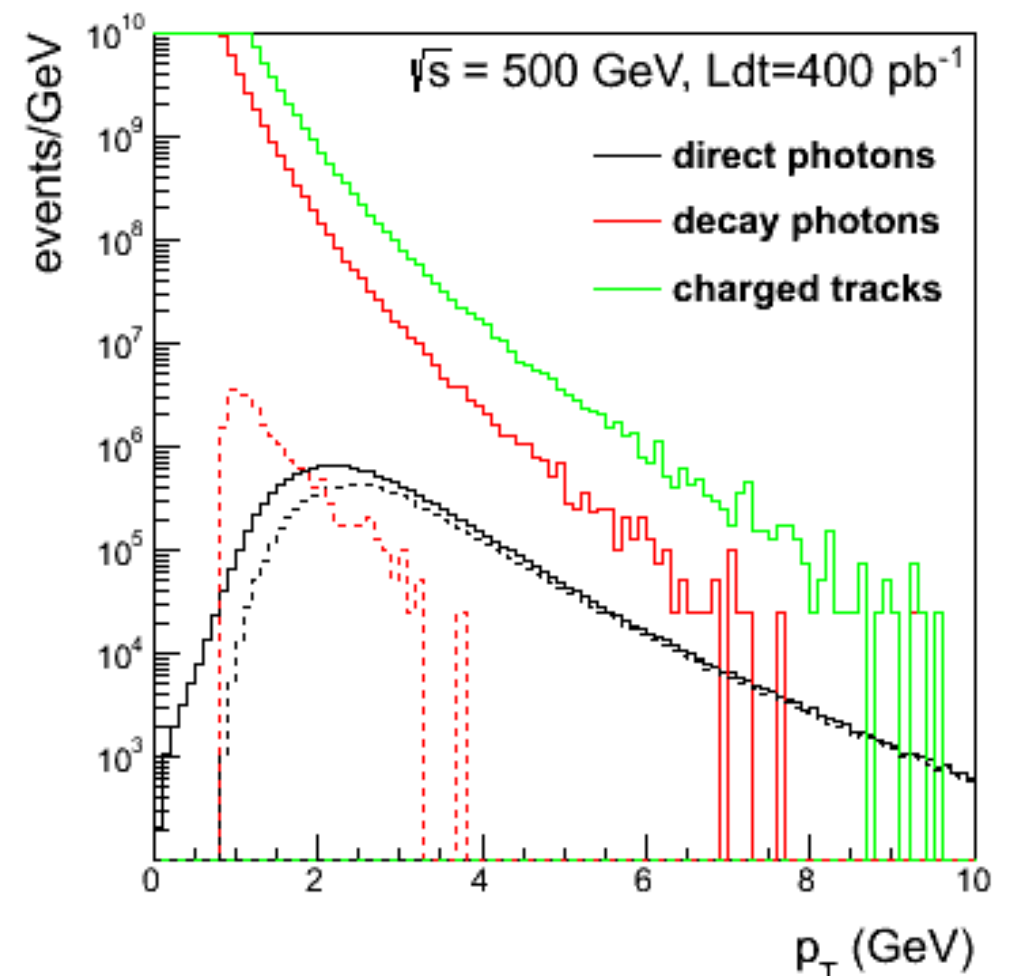
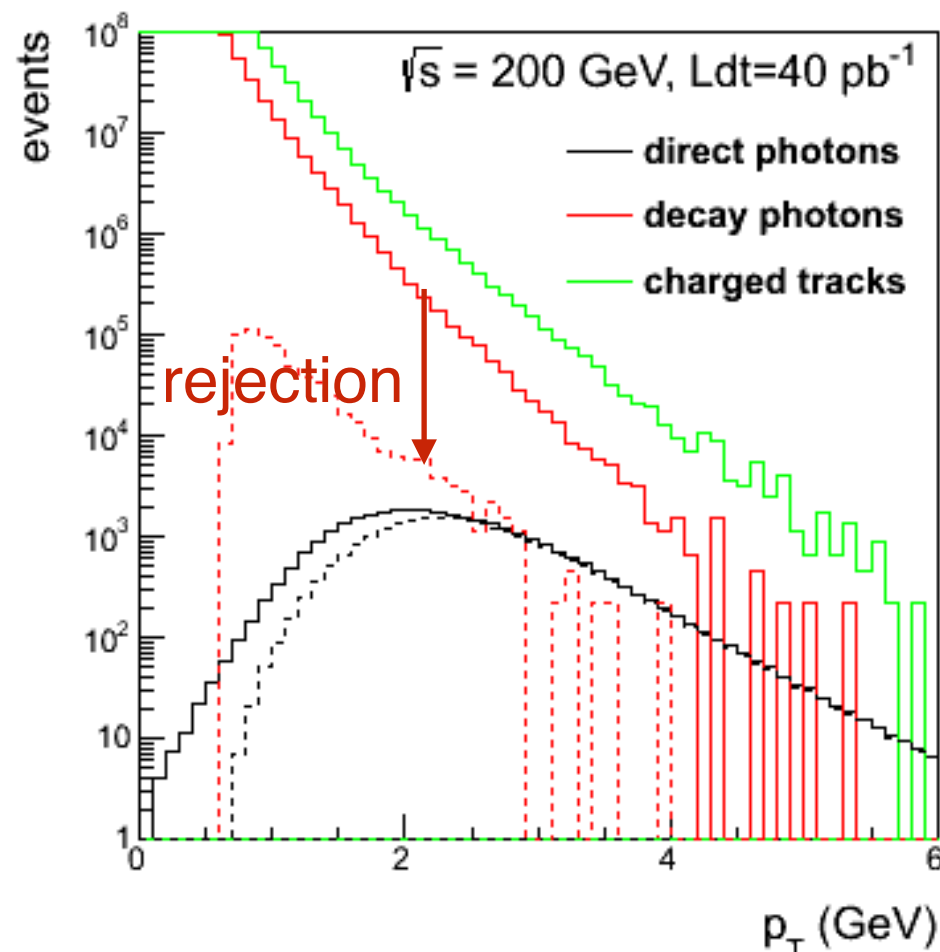


Post-shower will adopt similar design; proposal being readied.

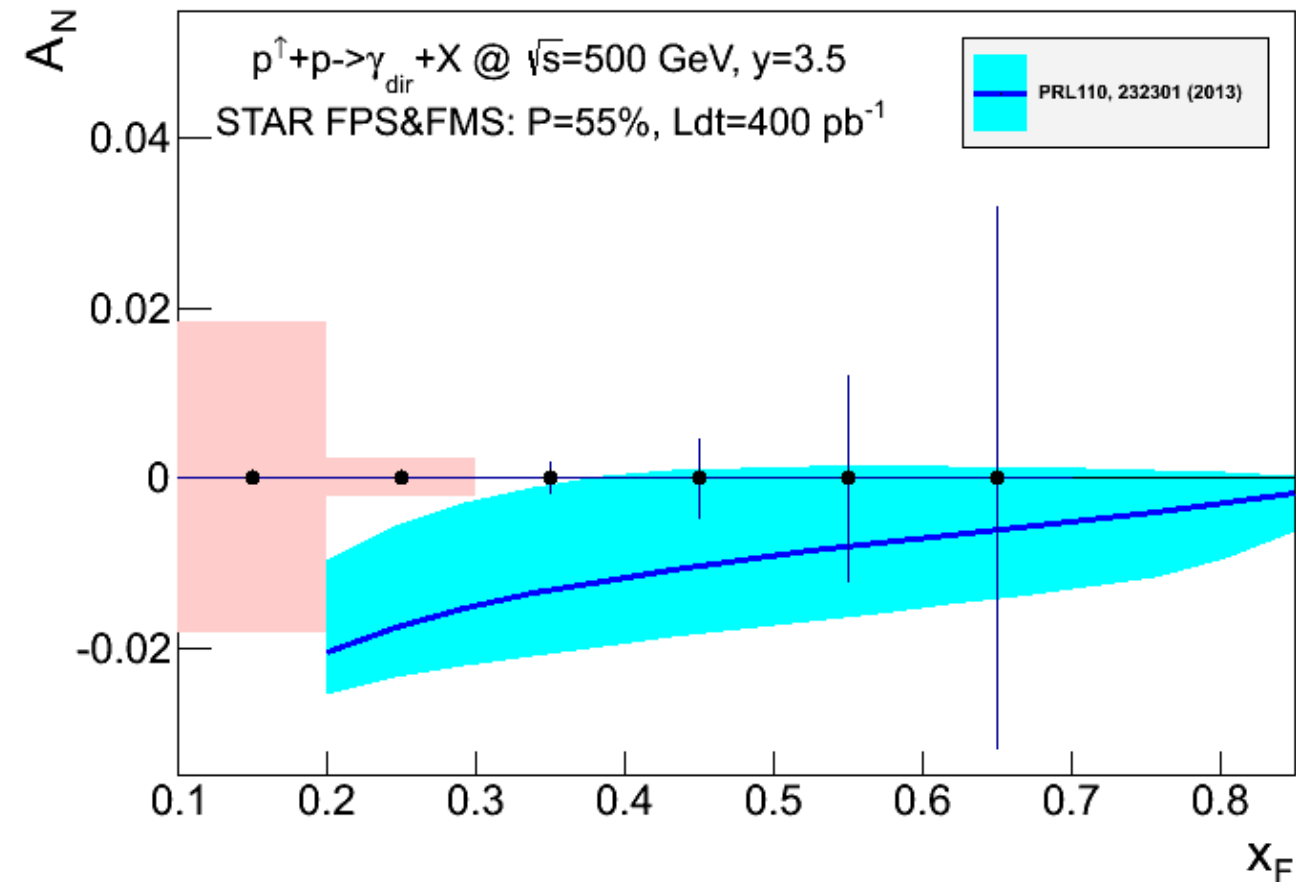
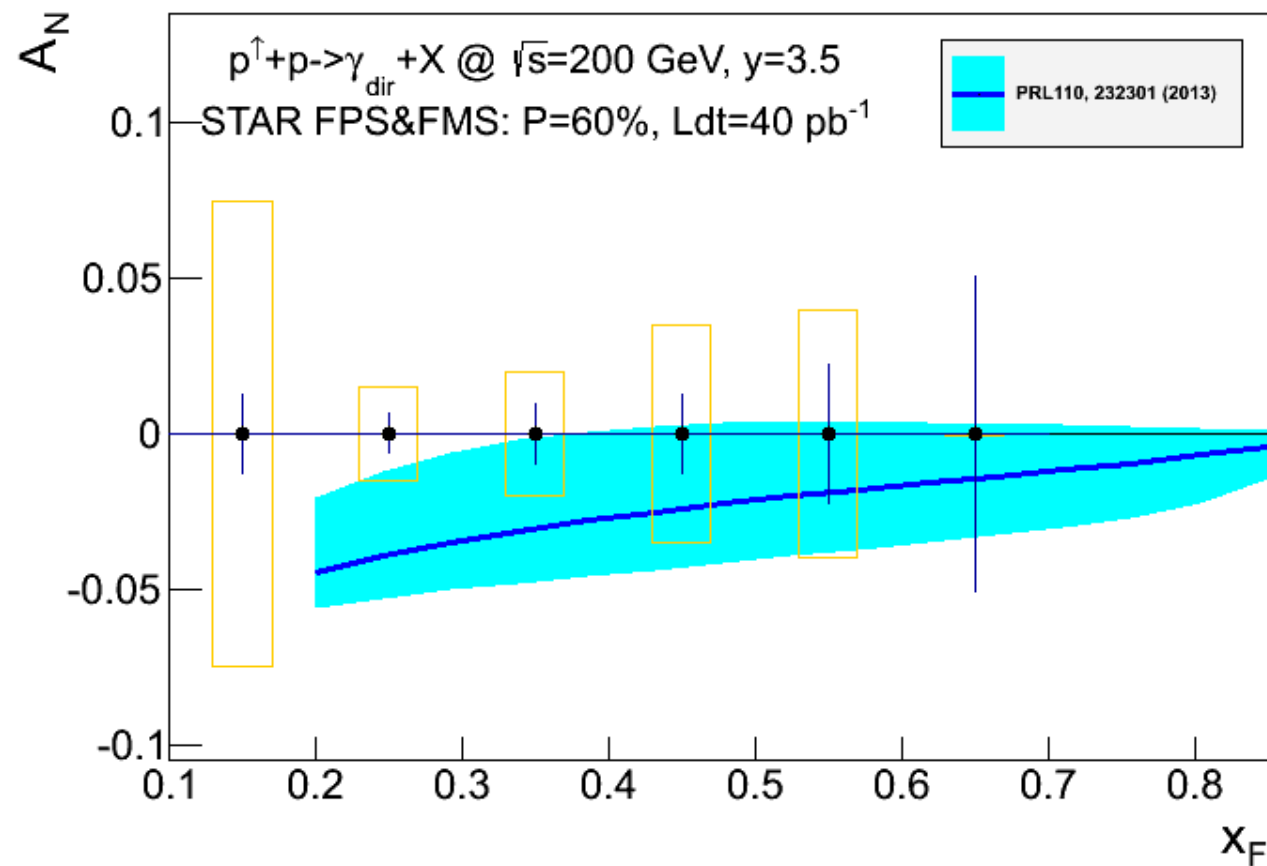
STAR Preshower (installed before Run-15)



3-layer pre-shower mounted directly in front of the FMS;
distinguish photons, electrons/positrons, charged hadrons.



STAR FMS+FPS - photon A_N



Sensitive to the “sign-change” in the twist-3 formalism,

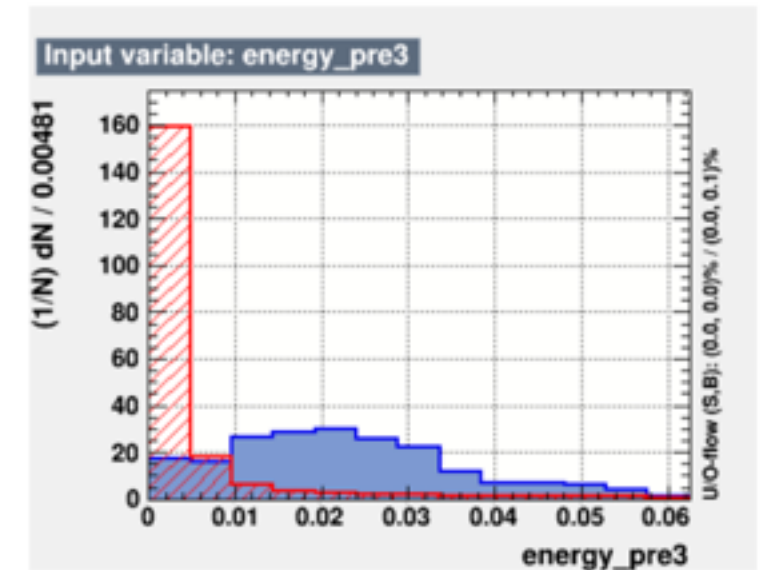
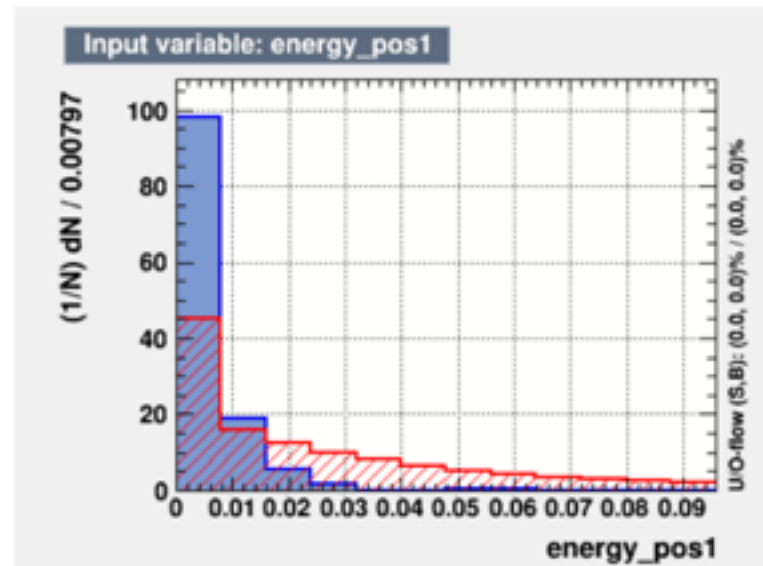
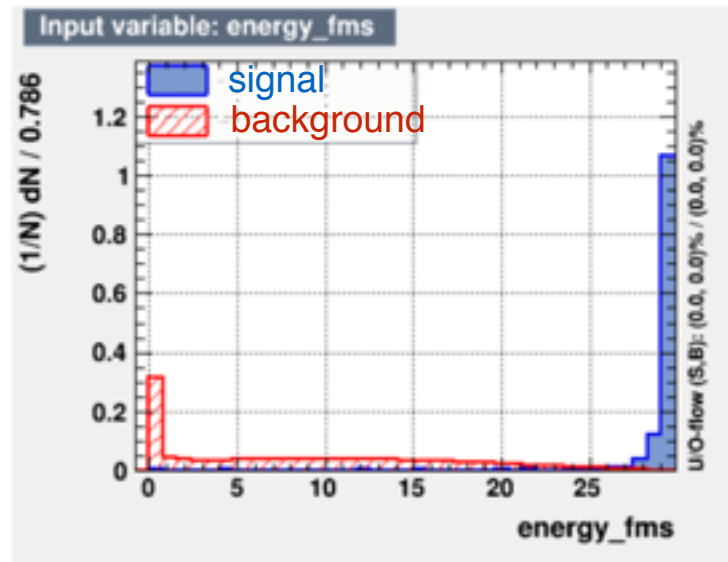
light valence quarks, at relatively high- x ,

twist-3 evolution, *not* TMD evolution.

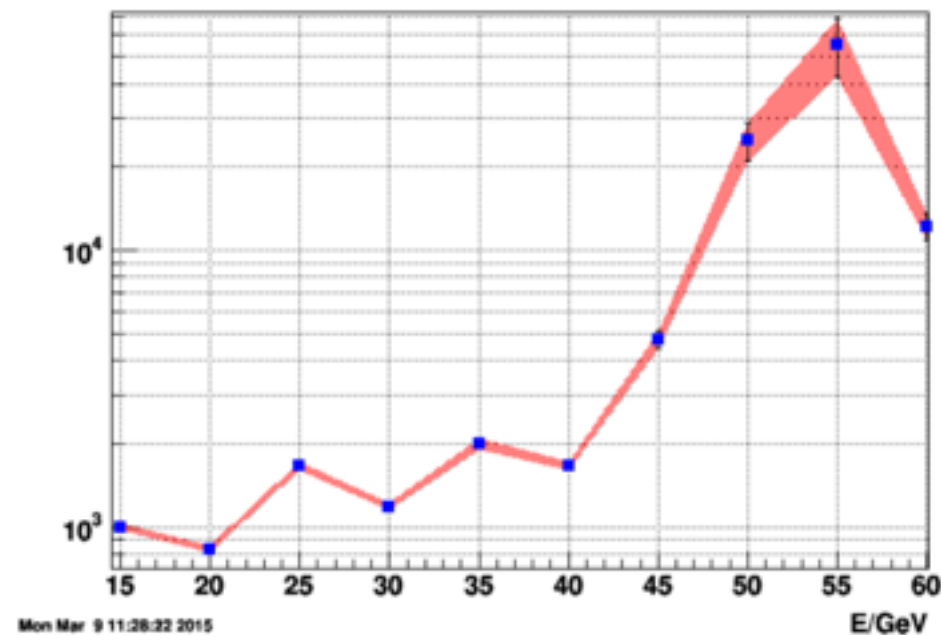
Constraining this evolution is one of the motivations for running in 2020+

STAR FMS+FPS+PSD - Drell-Yan

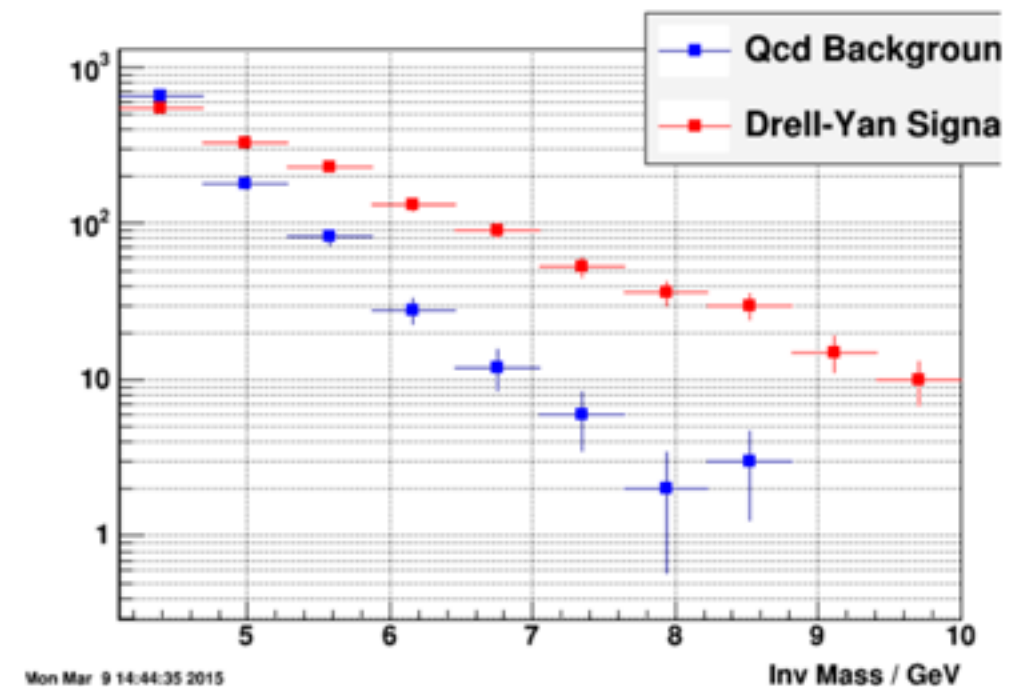
Multi-variant analysis using Boosted Decision Trees:



Suppression factors

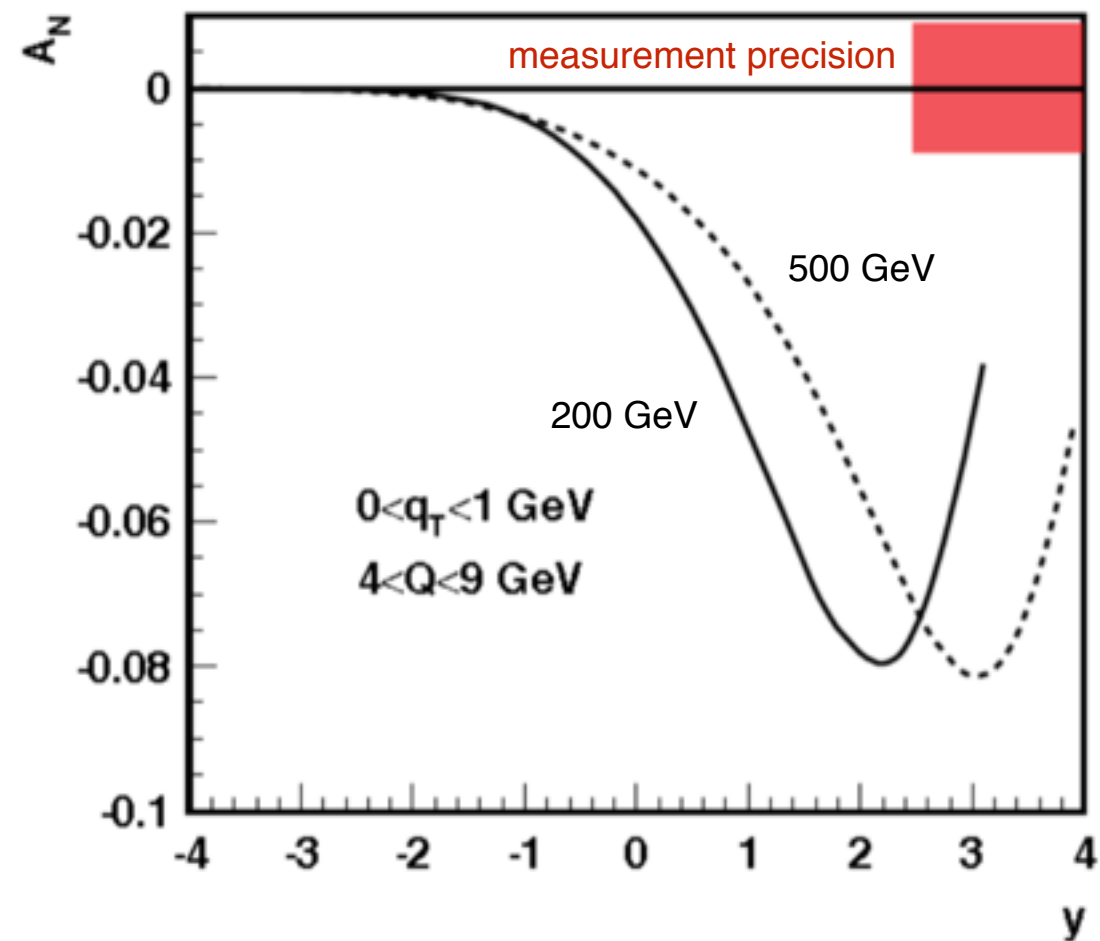


Signal and Background

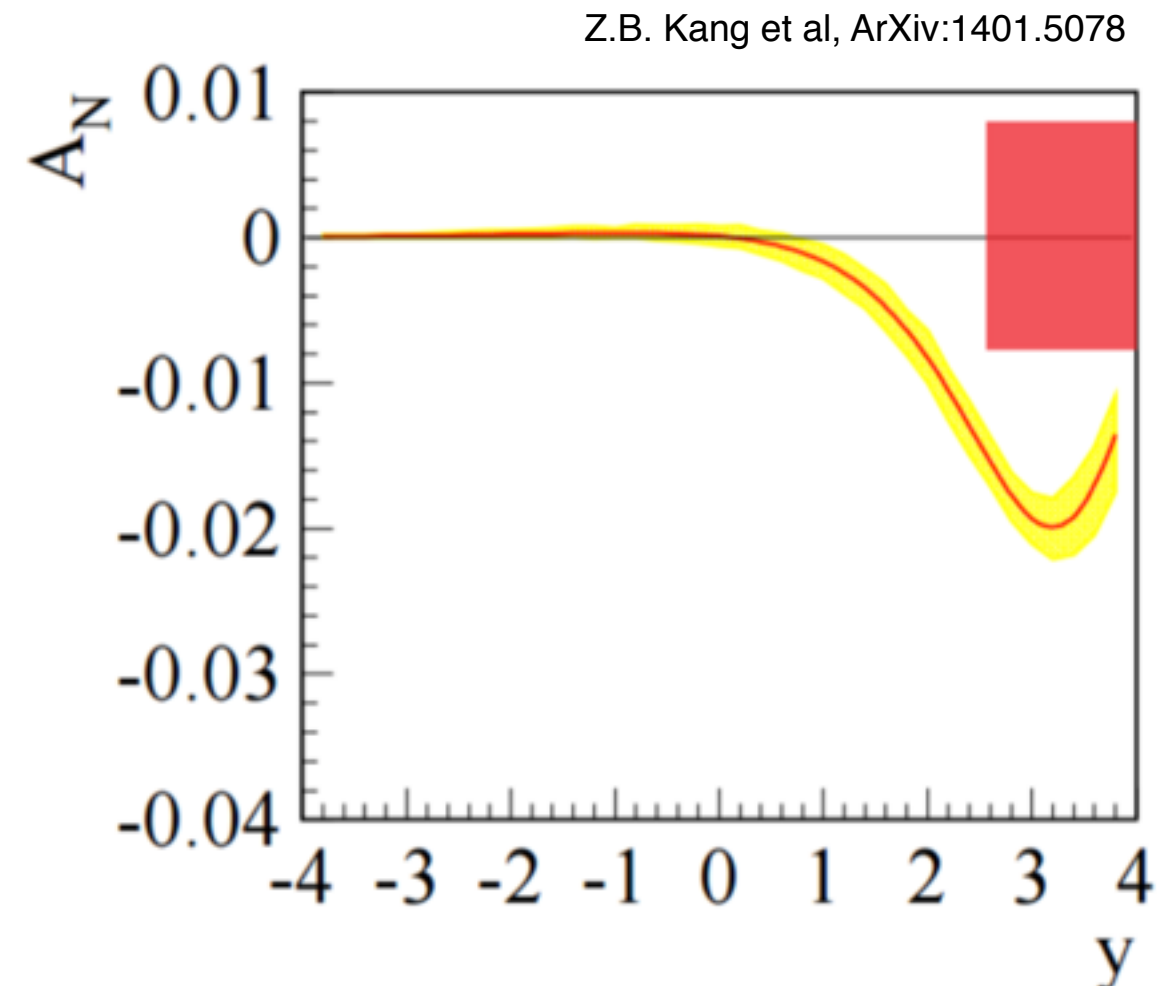


Drell-Yan A_N - STAR Prospects for Run-17

No TMD evolution



With TMD evolution



W, Drell-Yan, and photon A_N

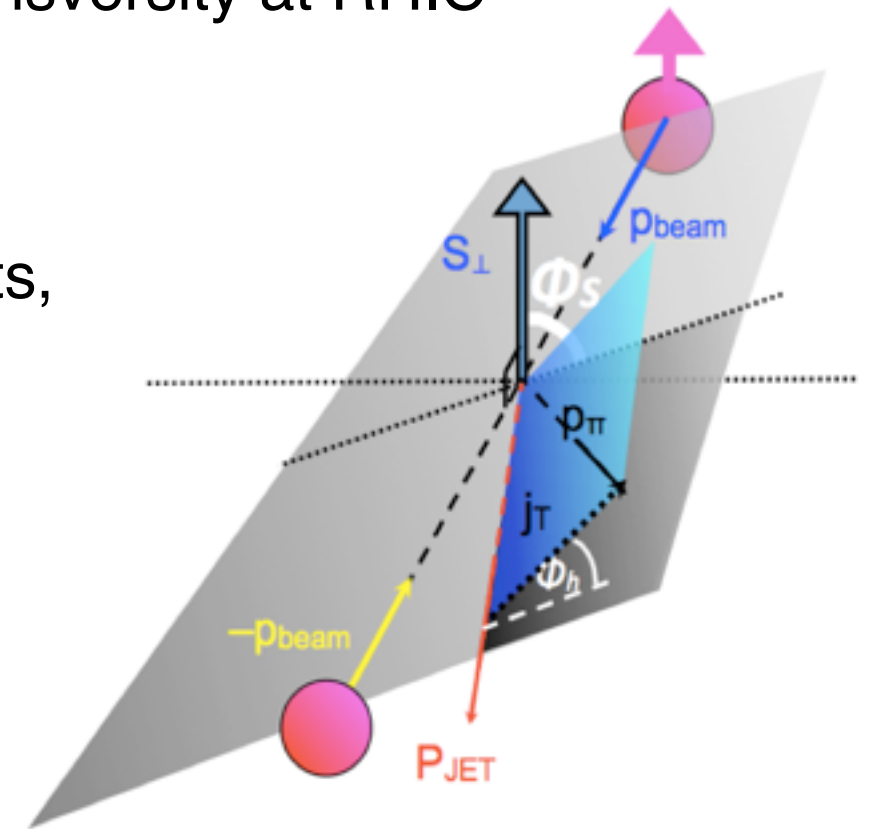
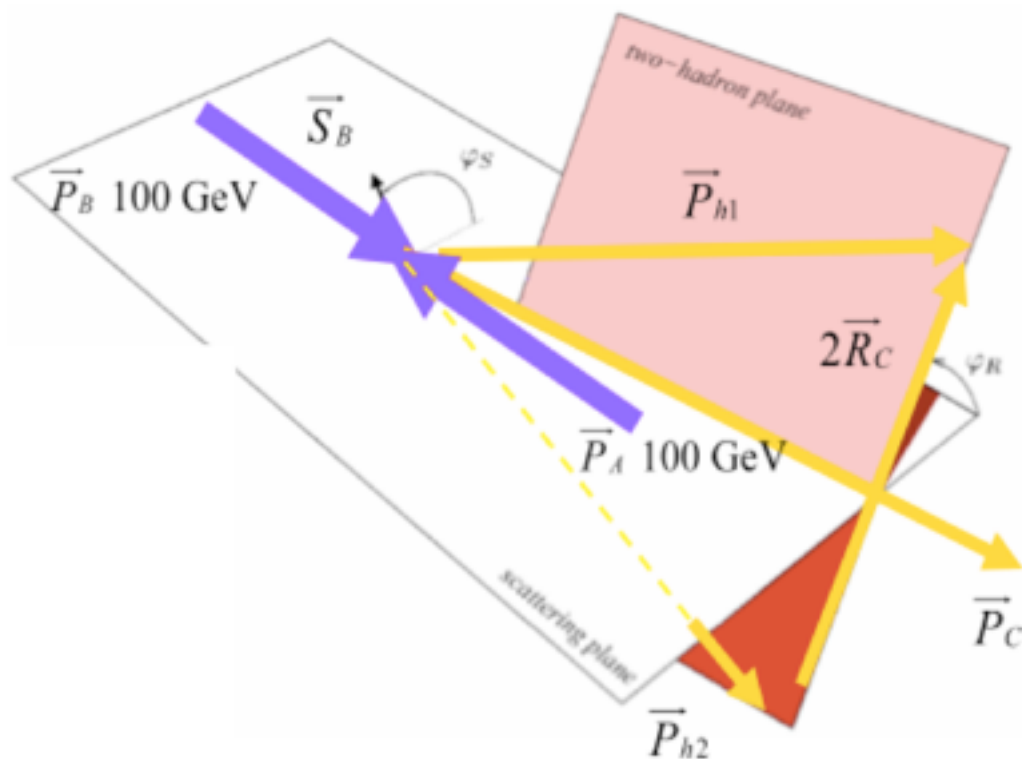
	$A_N(W^{+/-}, Z^0)$	$A_N(DY)$	$A_N(\gamma)$
Sensitive to Sivers effect non-universality through TMDs	Yes	Yes	No
Sensitive to Sivers effect non-universality through Twist-3 $T_{q,F}(x,x)$	No	No	Yes
Sensitive to TMD or Twist-3 evolution	Yes	Yes	Yes
Sensitive to sea quark Sivers or ETQS function	Yes	Yes ($x < 10^{-3}$)	No
Detector upgrade needed	No	Yes FMS post-shower	No
Biggest experimental challenge	Integrated luminosity	Background suppression Integrated luminosity	----

Table 2-2: Summary of all the processes accessible in STAR to access the sign change of the Sivers function.

STAR - Quark Transversity

At least two methods can provide sensitivity to quark transversity at RHIC

1. spin-dependent modulation of hadron yields within jets,



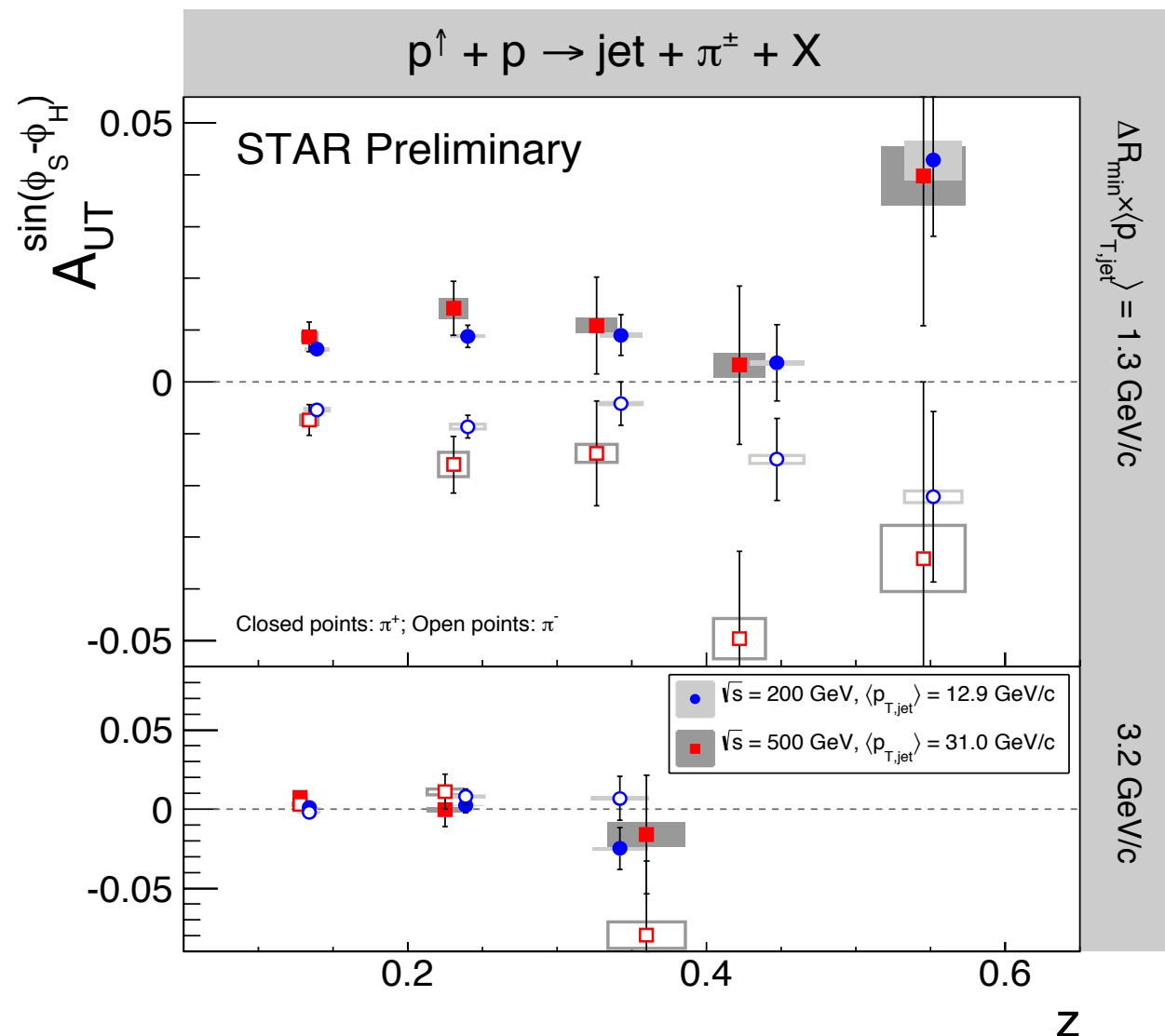
$$h_1(x) \otimes H_1^\perp(z, j_T)$$

2. di-hadron correlation measurements couple transversity with interference-fragmentation.

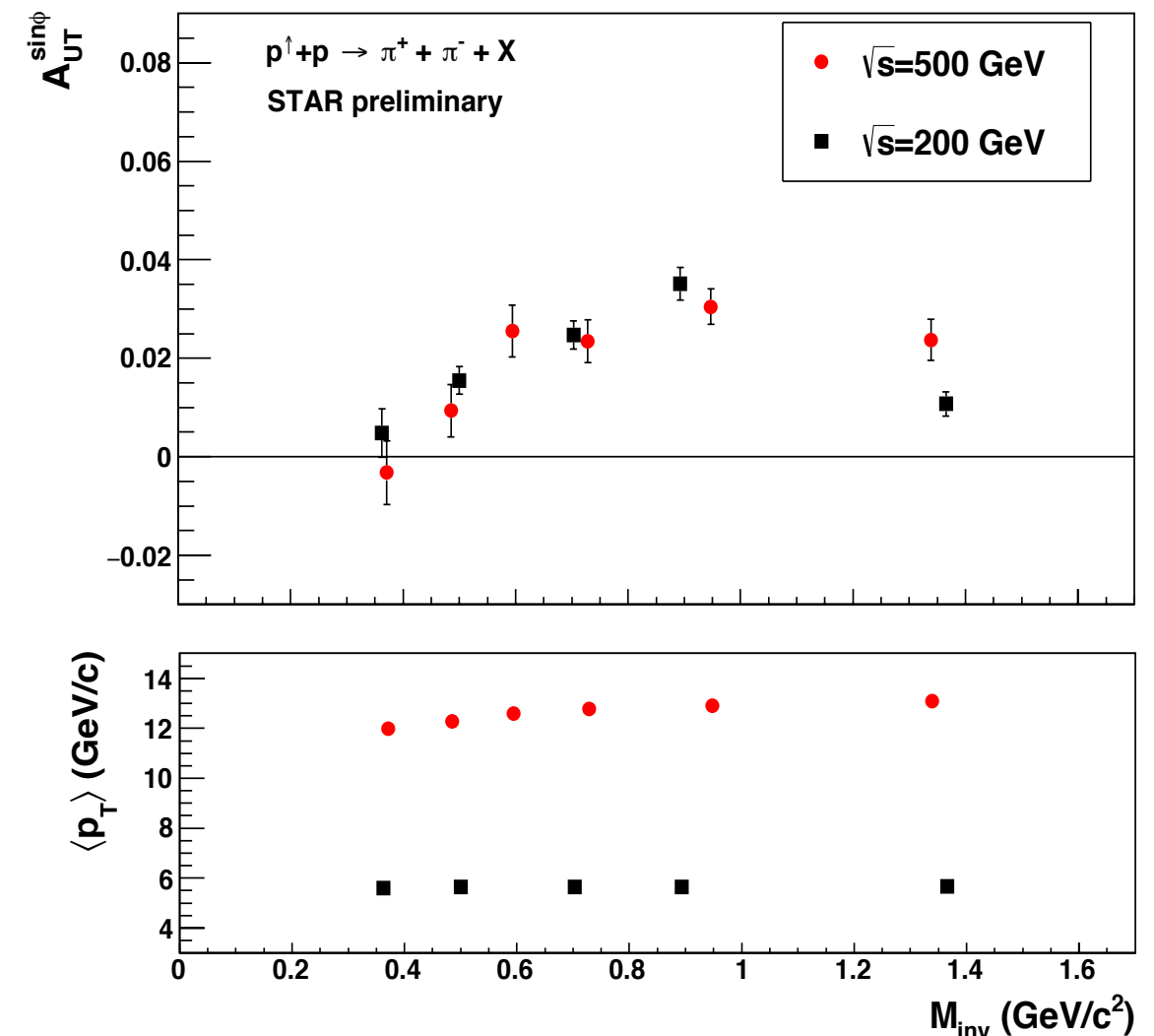
Both methods have been pursued and have delivered initial results...

STAR - Quark Transversity

azimuthal modulation within the jet



interference fragmentation



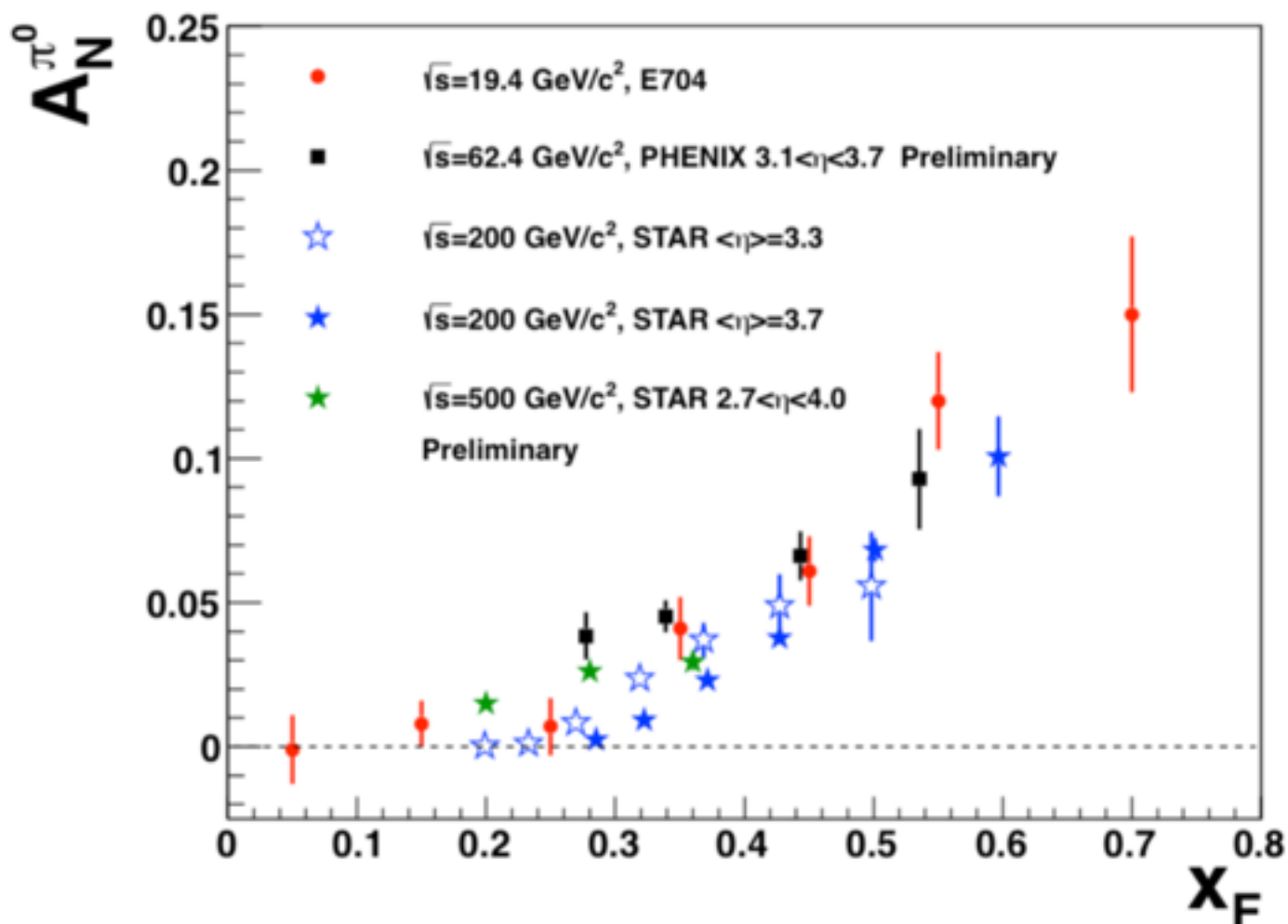
Sensitivity to quark transversity and *polarized* fragmentation,

200 and 500 GeV results are similar; is TMD evolution in FF small?

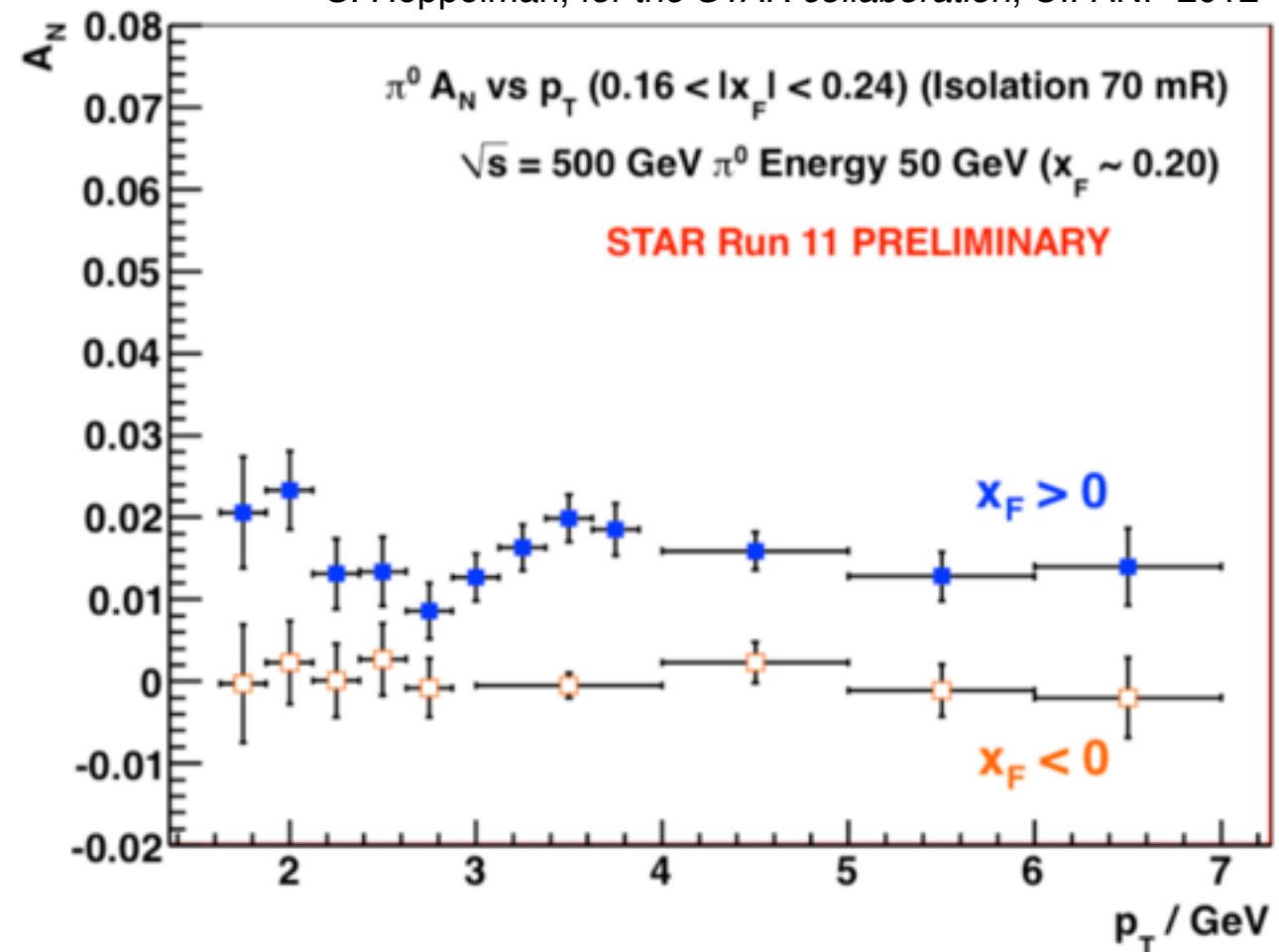
Non-zero observations open a path to nuclear modification of polarized fragmentation,
first analyses in progress,

Particle-identification key to further surprises? Theoretical/phenomenological input sought.

STAR's progress on the E704 legacy



S. Heppelman, for the STAR collaboration, CIPANP 2012



The rise of neutral-pion A_N with x_F is near-constant with \sqrt{s} , to highest $\sqrt{s} = 510$ GeV,

The origin remains largely unknown; contributions from Sivers, Collins effects?

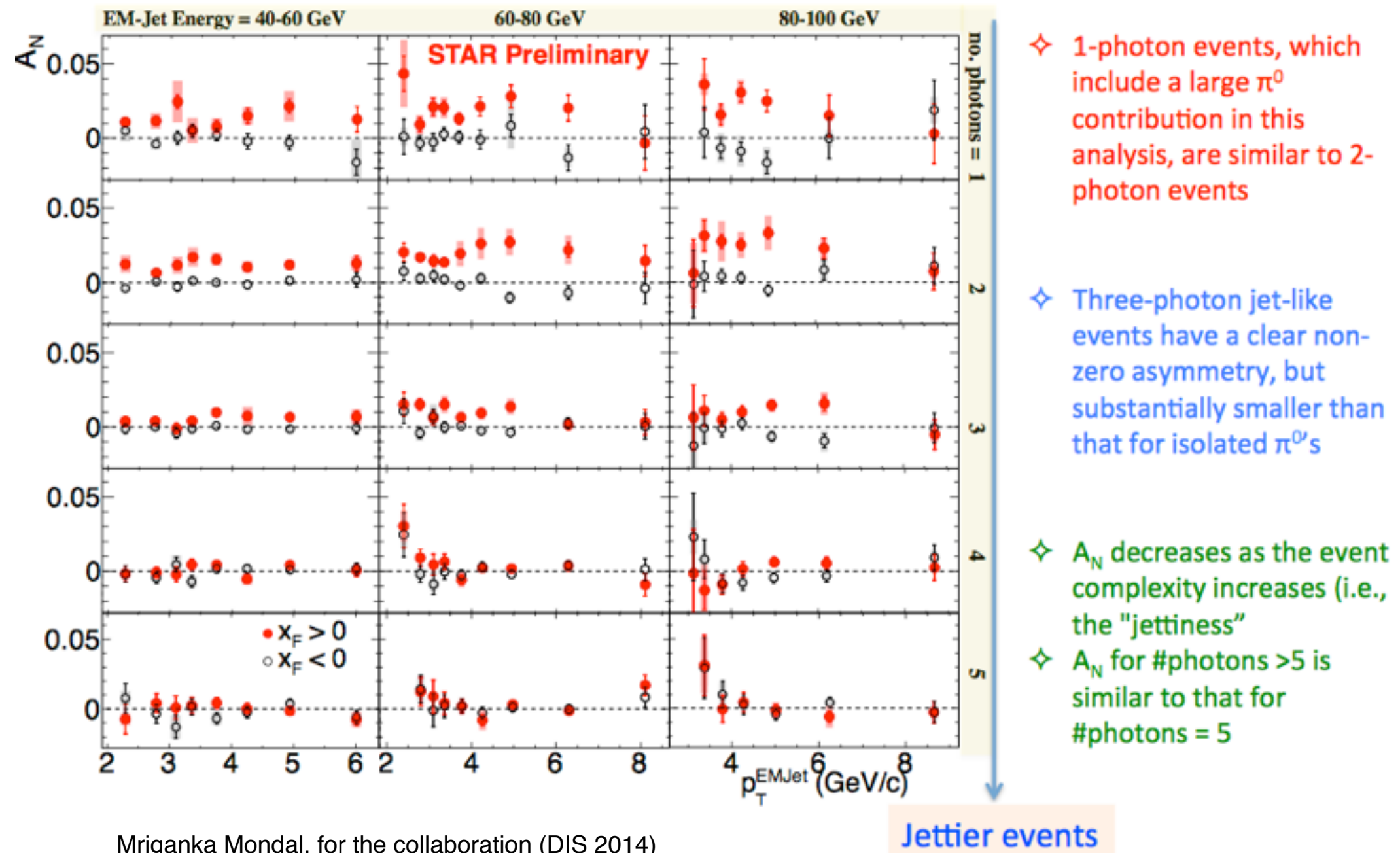
higher twist?

other production mechanism(s)?

Large acceptance and qualitatively new measurement capability appear key to a resolution.

STAR's progress on the E704 legacy

The puzzle continues...



Mriganka Mondal, for the collaboration (DIS 2014)

and points to a need for qualitatively new instrumentation and measurements, Low-multiplicity observation, consistent with a diffractive production mechanism, STAR Roman Pots will directly measure diffractive A_N . Initial analyses in progress.

STAR's progress on the E704 legacy

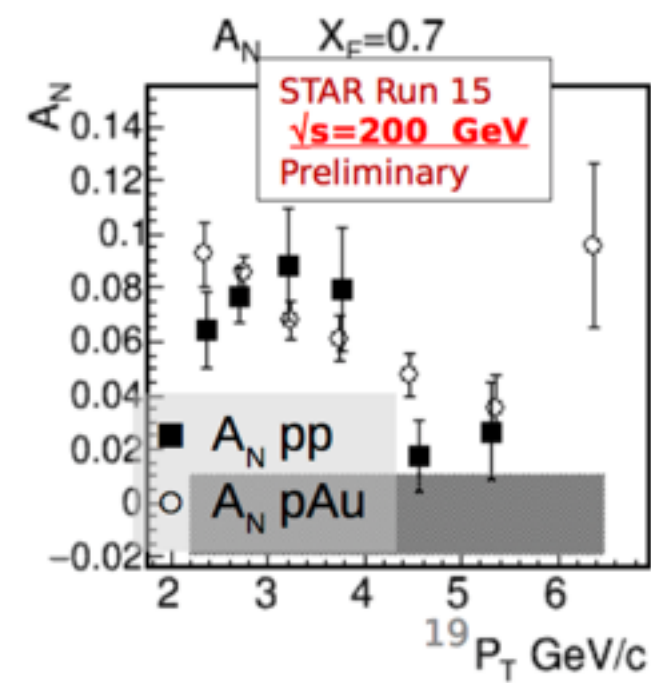
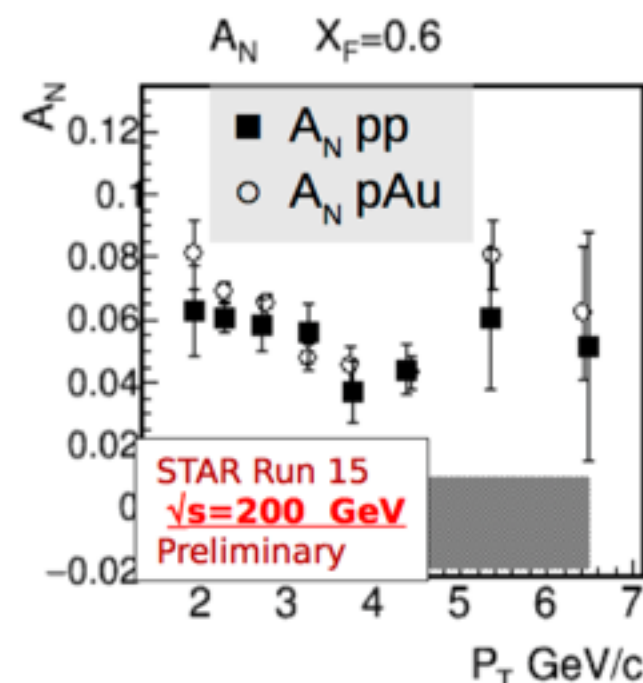
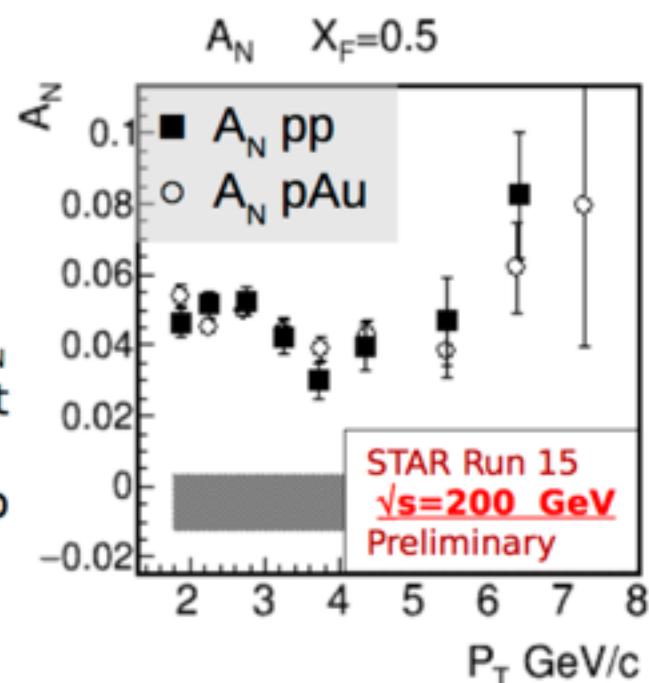
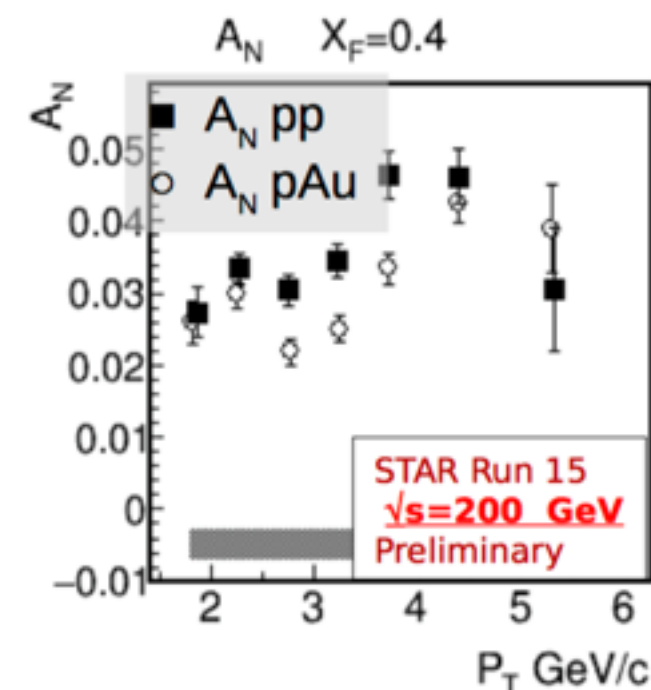
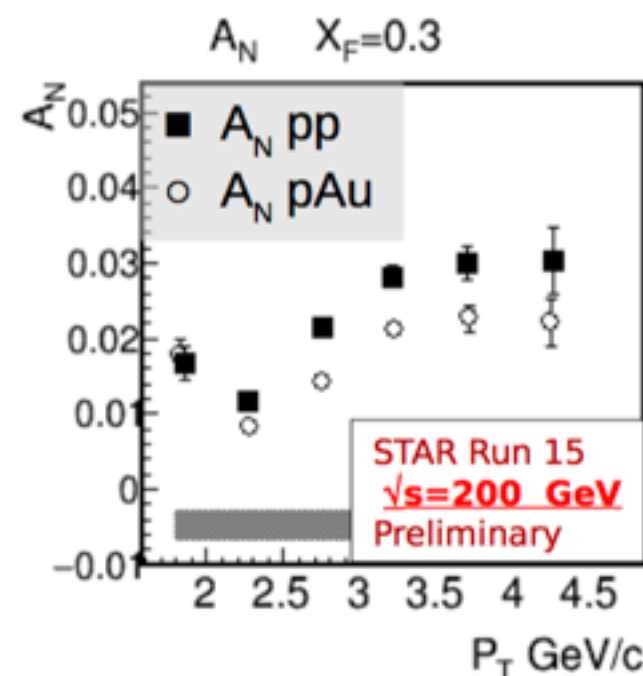
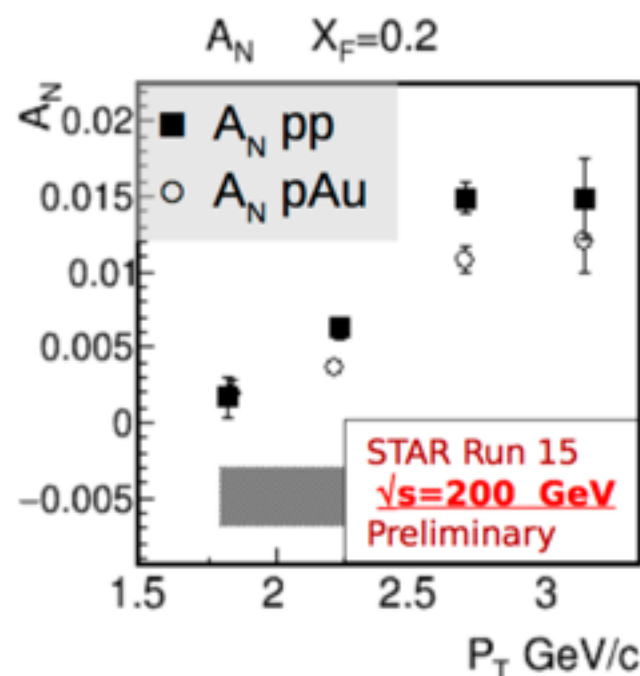
First observations from p+Au:

Error bars represent statistical errors only.

Luminosity:
pAu=204.6 nb⁻¹
pp=34.8 pb⁻¹

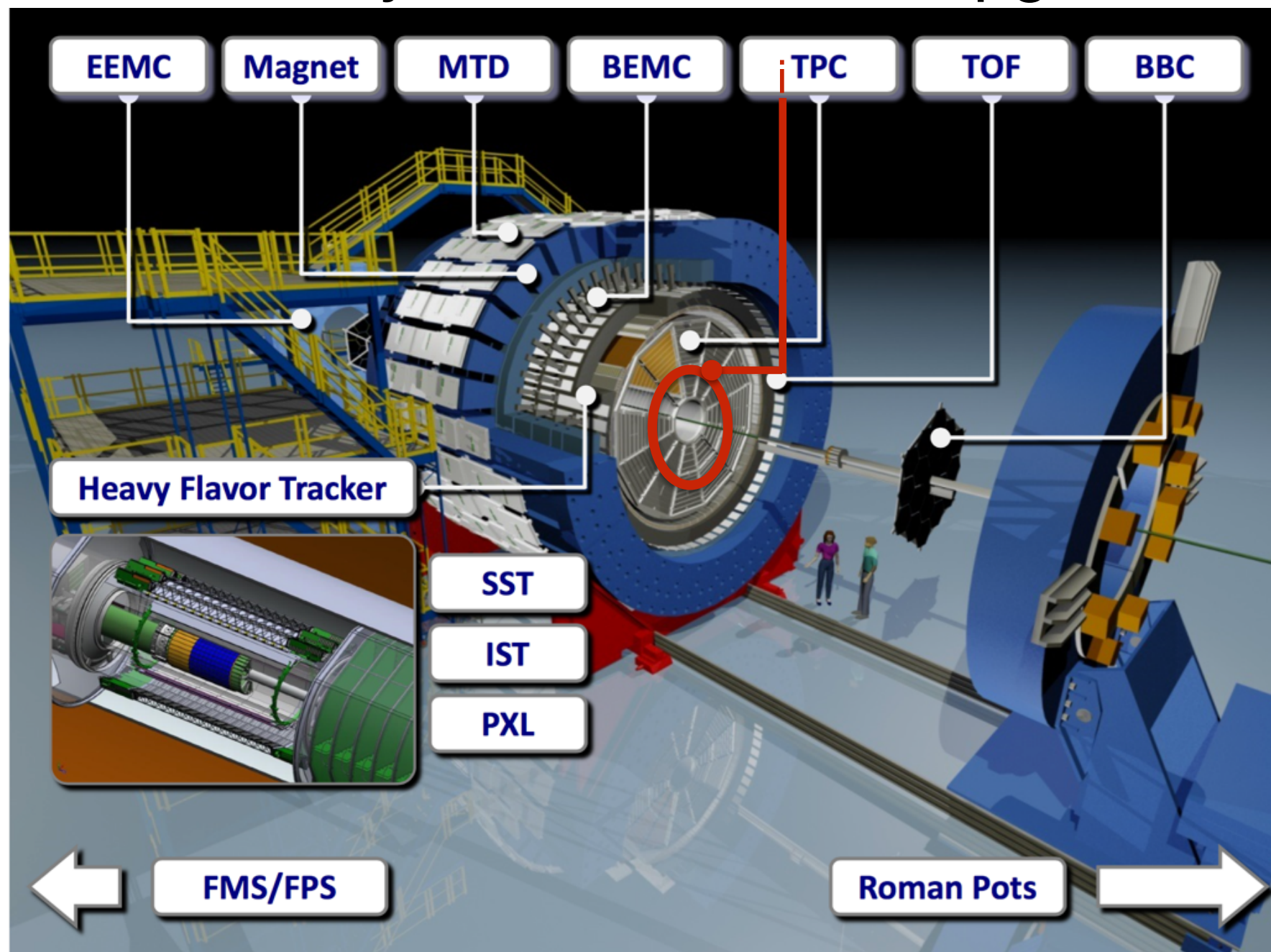
Average Polarization:
pp 55.6 ± 2 %
pAu 60.4 ± 2 %

Shaded bands represent systematic uncertainty, dominated by dependence of A_N on observed East BBC energy (gold or proton breakup charge multiplicity)



No evidence for the sizable nuclear effects predicted in 2-to-2 saturation approaches.

STAR beyond 2017 - iTPC upgrade



BES-II driven proposal to upgrade the 24 inner TPC sectors to:

- increase the segmentation on the pad planes,
- renew inner sector wires.

Cost, schedule and risk review successful.

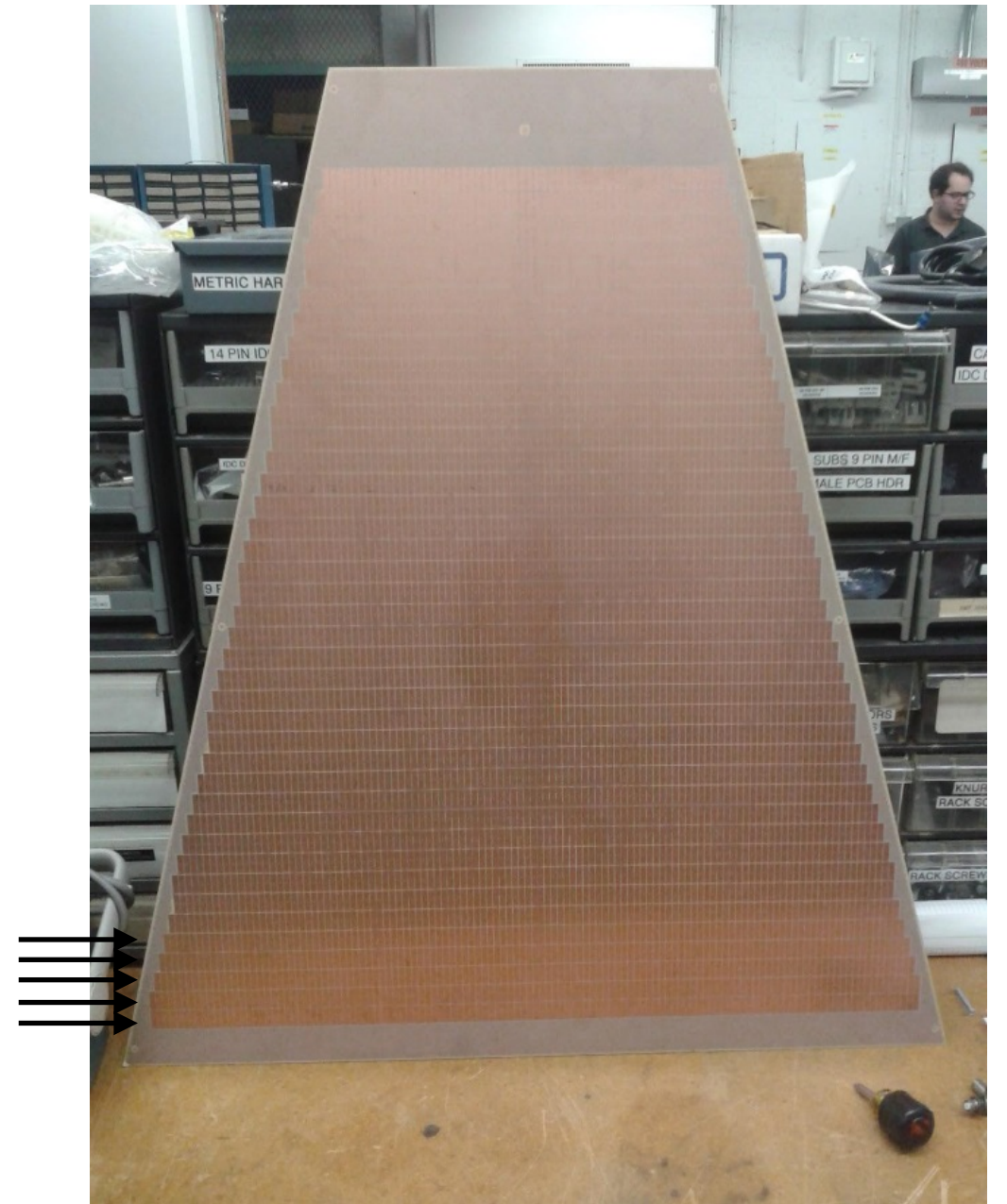
STAR beyond 2017 - iTPC upgrade

Existing (spare) inner TPC sector

iTPC prototype pad-plane (tested)

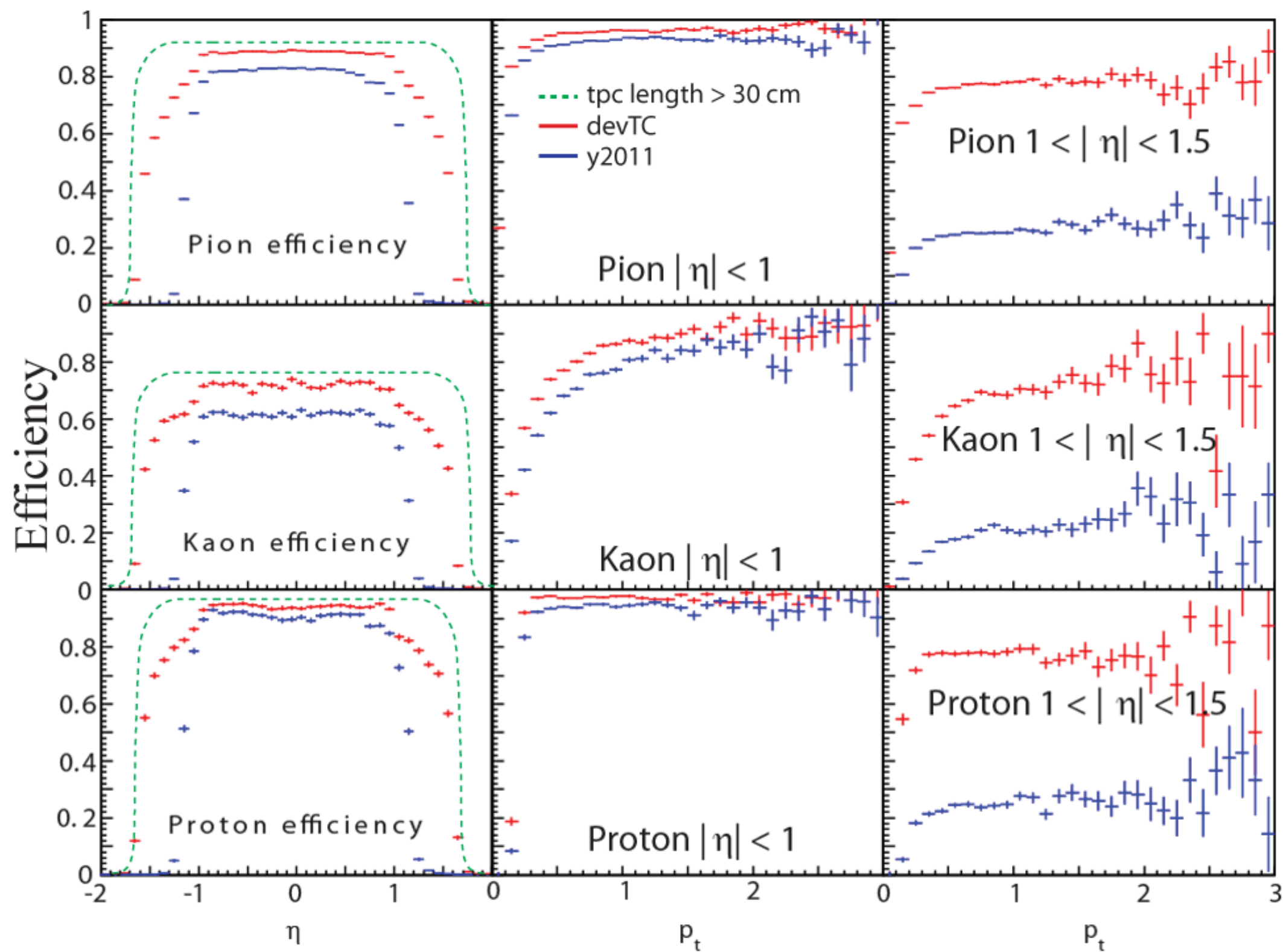


widely spaced ($> 5\text{cm}$) pad-rows

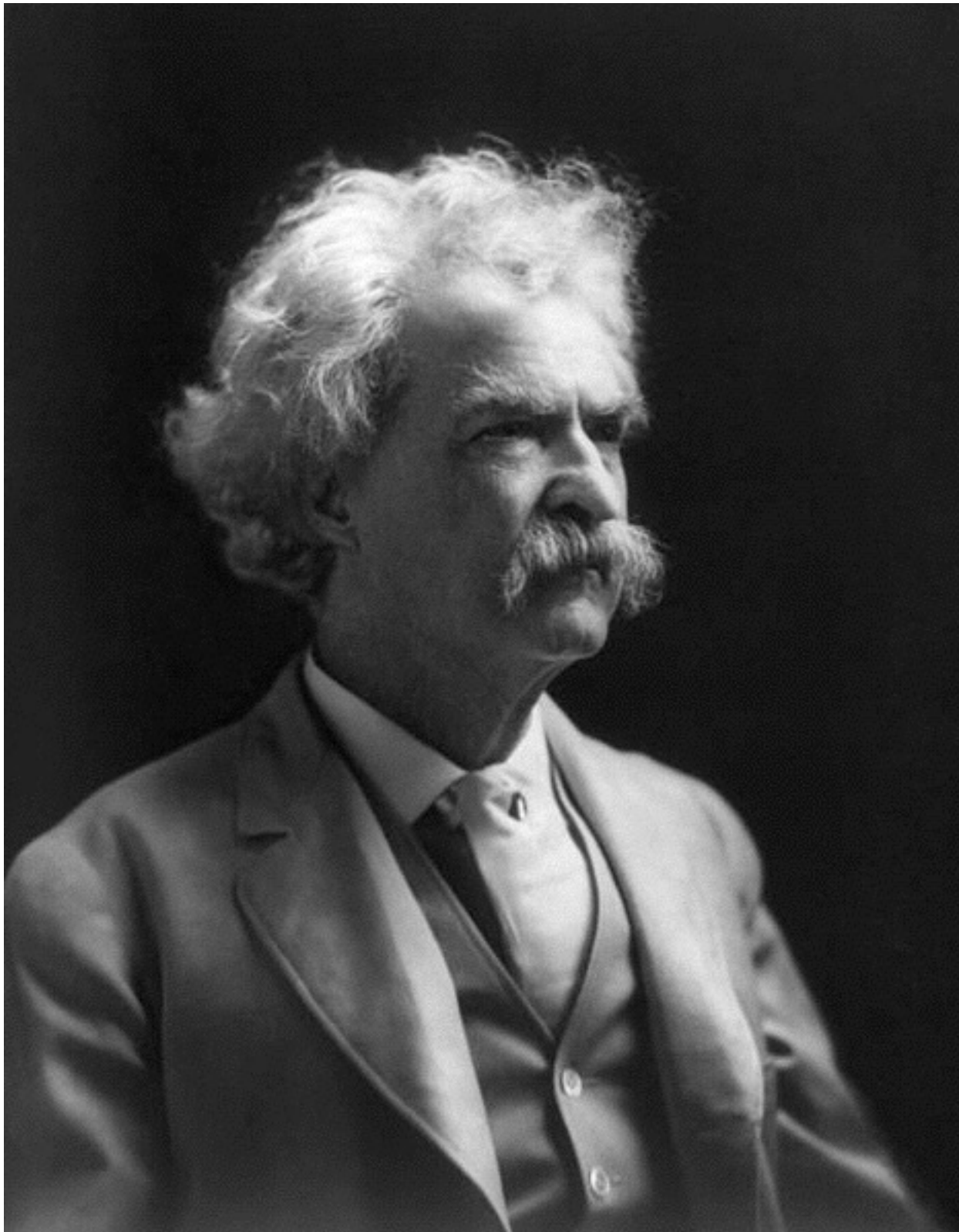


Upgrade is to increase the number of inner readout channels by a factor ~ 2 (optimized), increase the sampled track length to $\sim 95\%$, and thereby improve efficiency, in particular at low p_T improve particle identification via dE/dx , extend analyzed acceptance to larger (absolute) pseudo-rapidities.

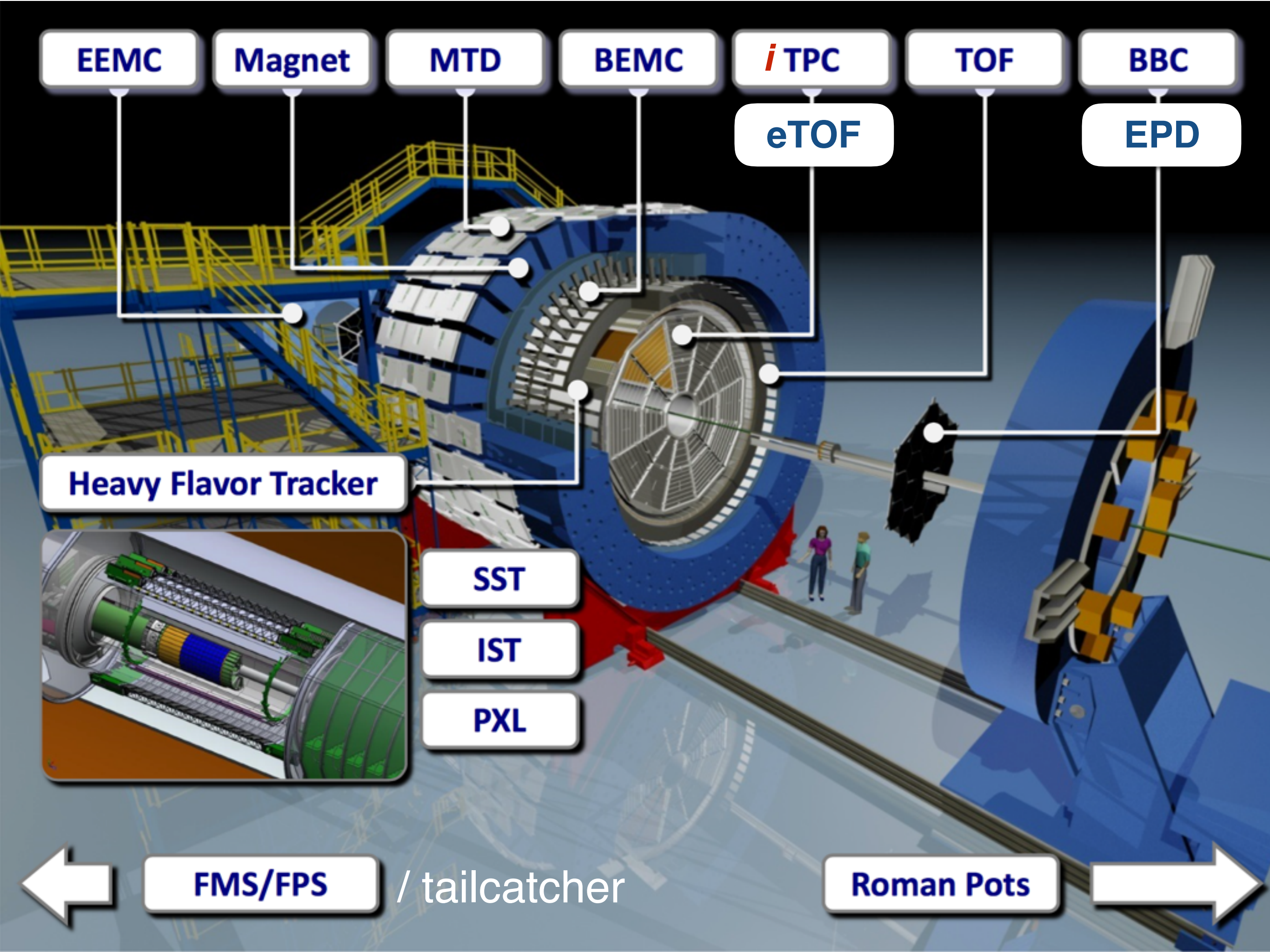
STAR iTPC - simulated performance



STAR after BES-II



*The report of my death
was an exaggeration.*



EEMC

Magnet

MTD

BEMC

iTPC

TOF

BBC

eTOF

EPD

Heavy Flavor Tracker

SST

IST

PXL

FMS/FPS

/ tailcatcher

Roman Pots



STAR between 2017 and EIC

	\sqrt{s} (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^+p @ 510$ 400 pb ⁻¹ 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ , W^\pm , Z^0 , DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/ Ψ in UPC	A_N^{DY} : Postshower to FMS@STAR None None
	2023	$p^+p @ 200$ 300 pb ⁻¹ 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. None None
	2023	$p^+Au @ 200$ 1.8 pb ⁻¹ 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, nuclear FF Dihadrons, γ -jet, h-jet, diffraction	$R_{pAu}(DY)$: Yes Forward instrum. None Yes Forward instrum.
	2023	$p^+Al @ 200$ 12.6 pb ⁻¹ 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl} : direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, nuclear FF Dihadrons, γ -jet, h-jet, diffraction	$R_{pAl}(DY)$: Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^+p @ 510$ 1.1 fb ⁻¹ 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. None
	202X	$\vec{p}\vec{p} @ 510$ 1.1 fb ⁻¹ 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/ γ -jets at $\eta > 1$	Yes Forward instrum.



ready

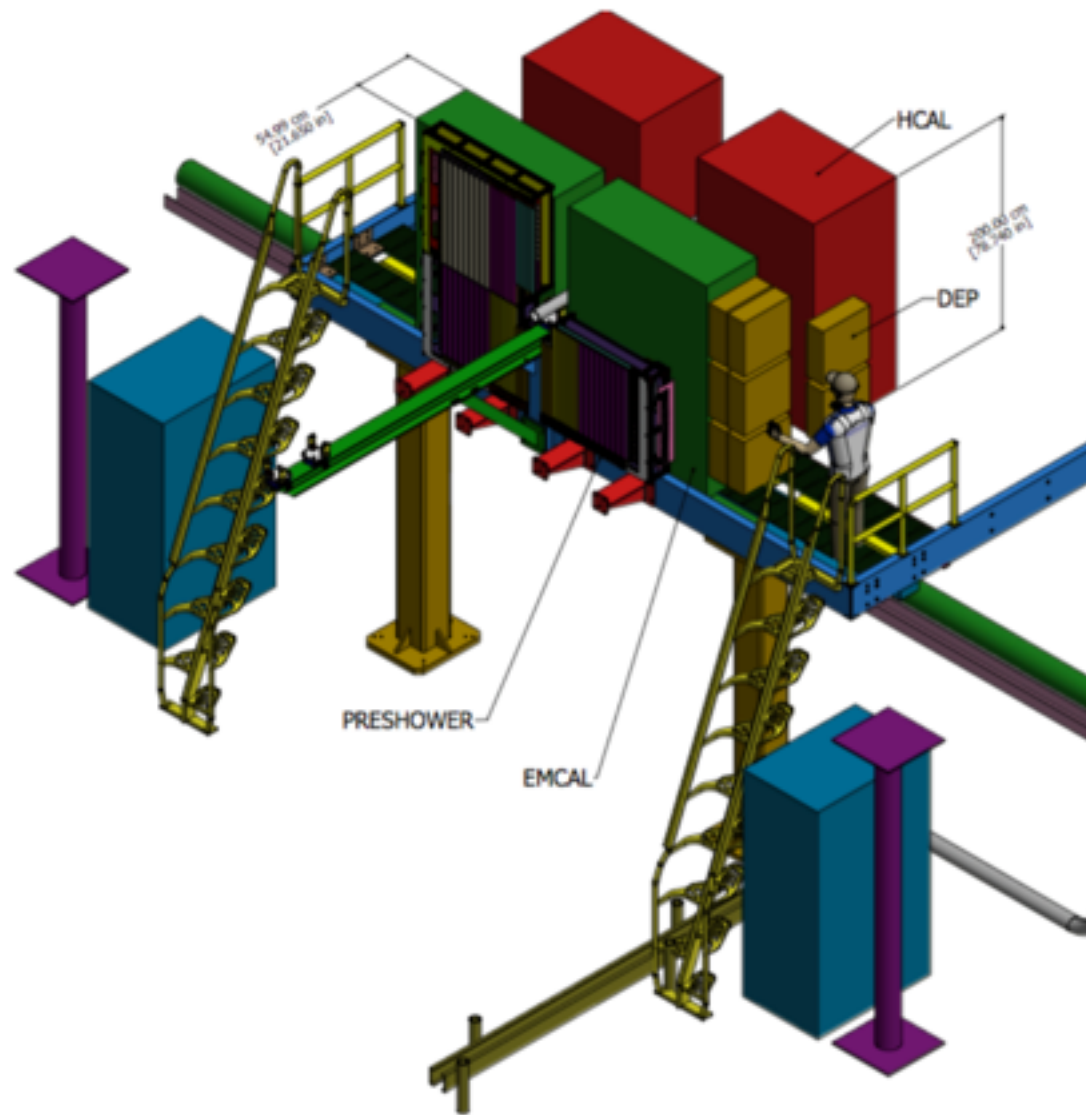
ready

ready

(ready)

Table 1-2: Summary of the Cold QCD physics program proposed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

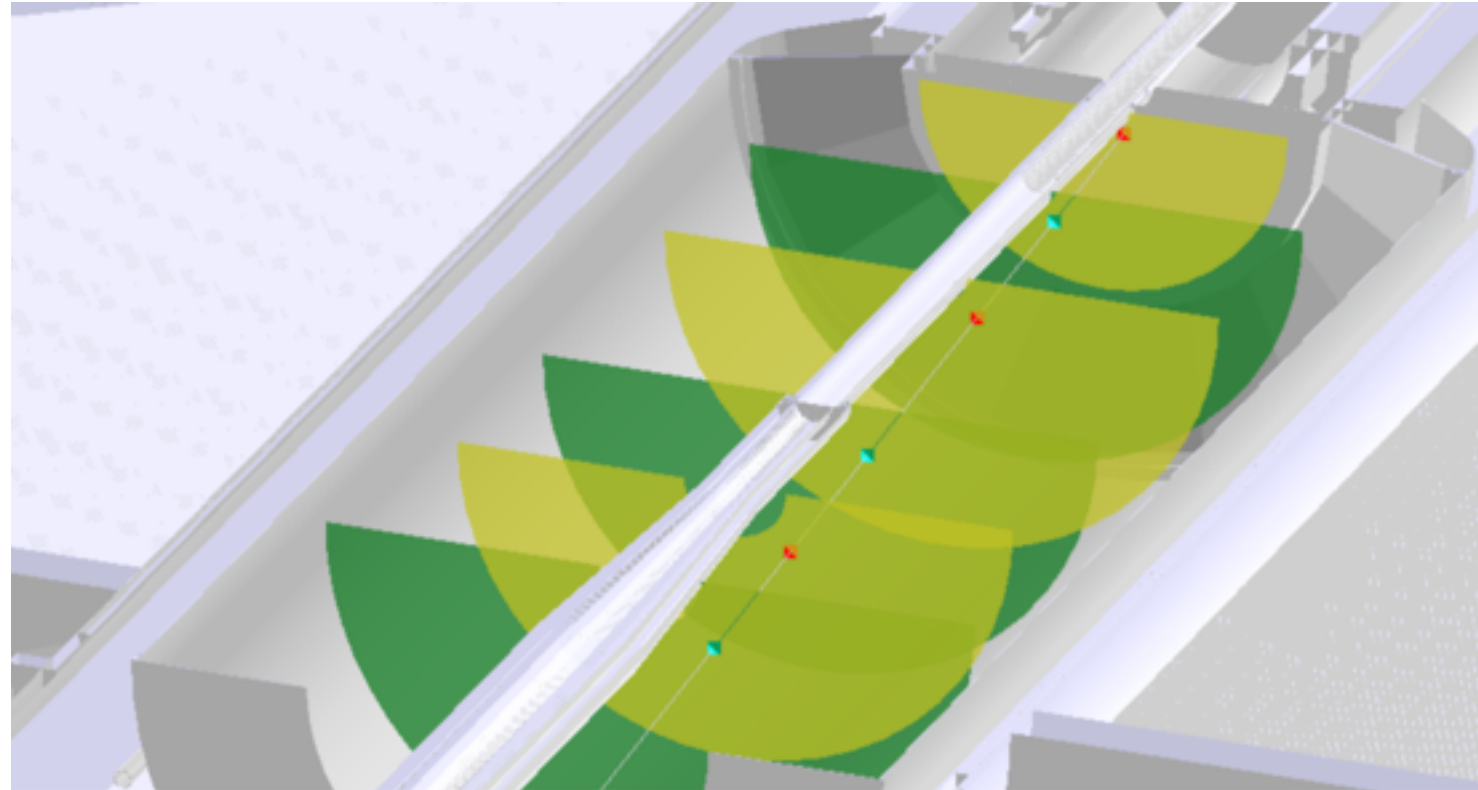
STAR FCS+FTS upgrade



was: W-powder EM-cal

now: re-use PHENIX eCAL

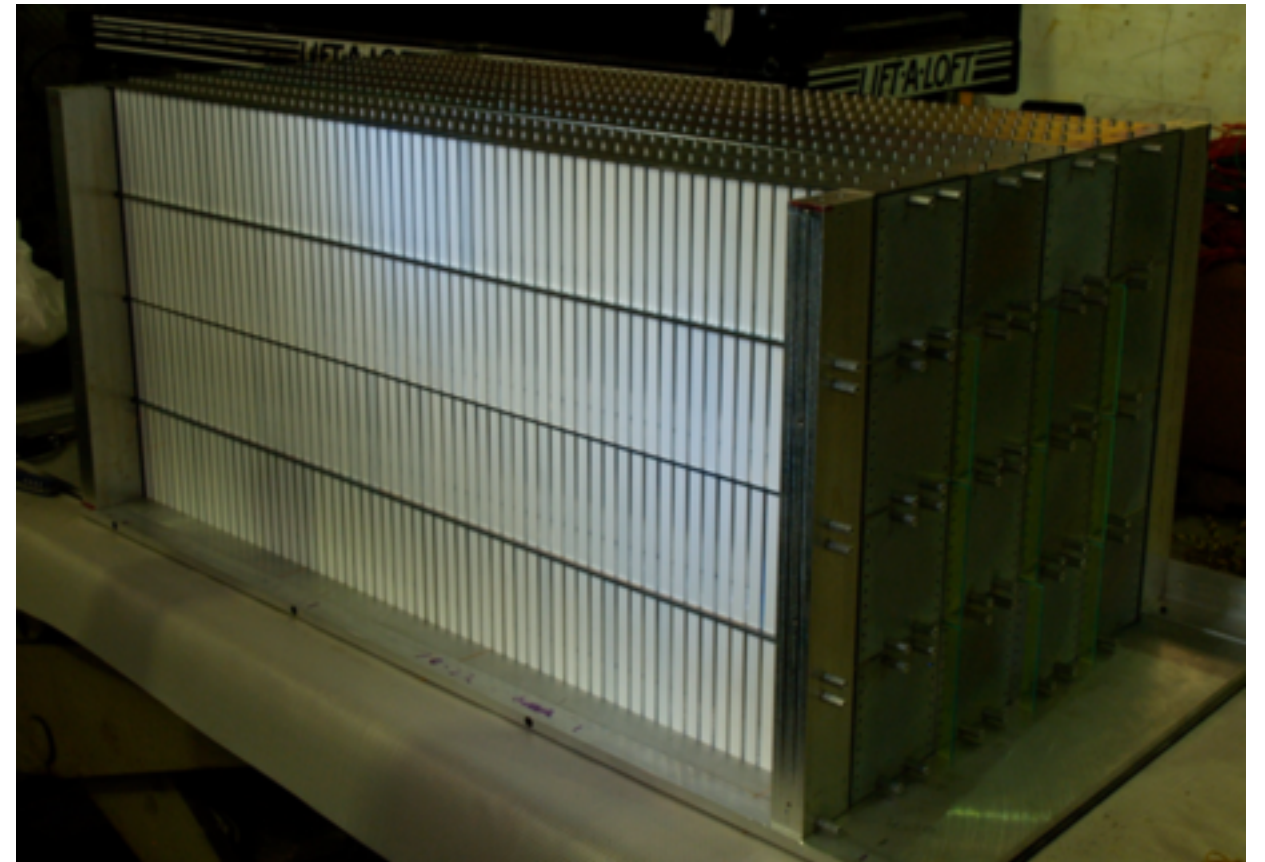
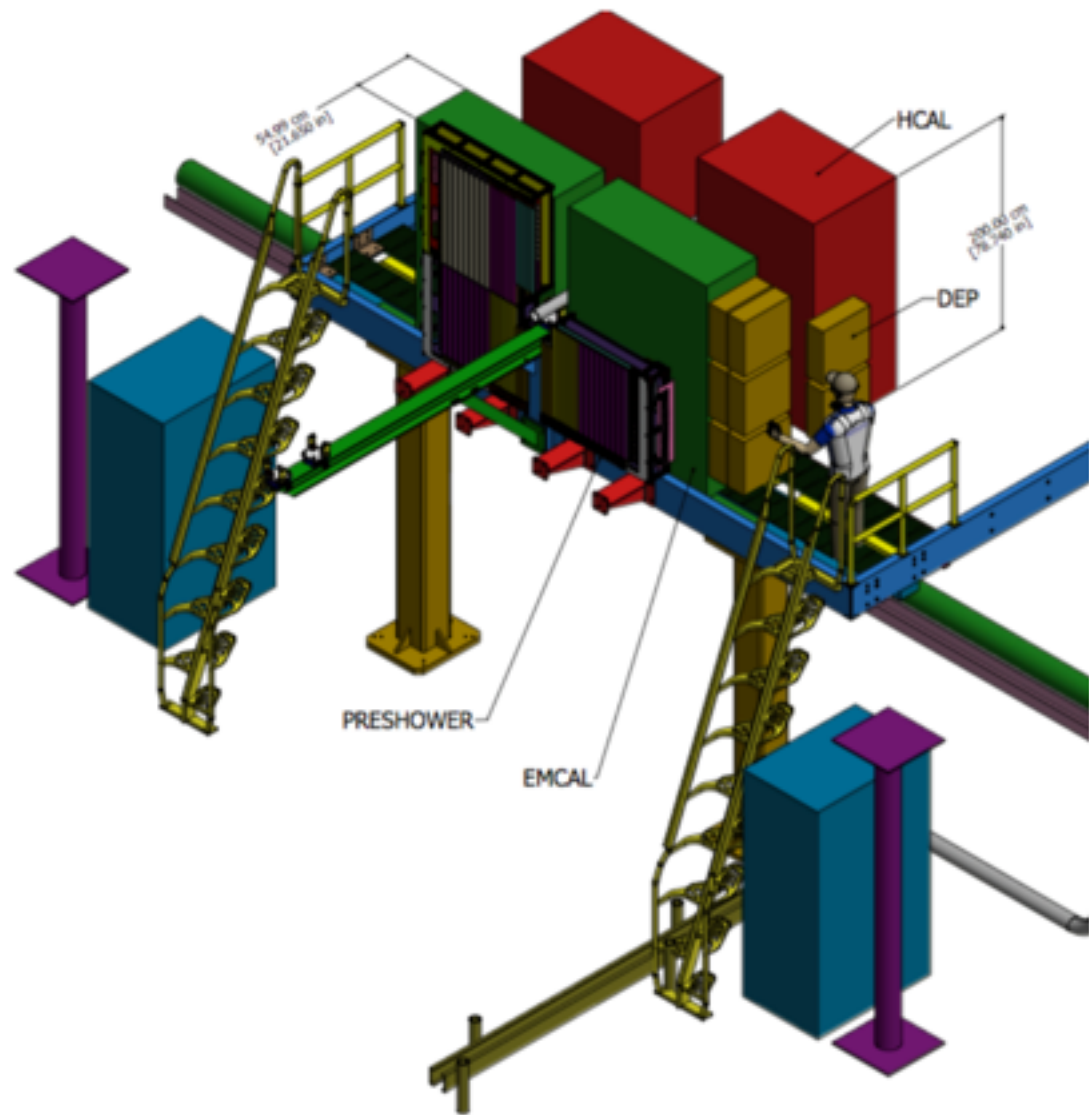
new HCAL, based on
STAR-EIC R&D



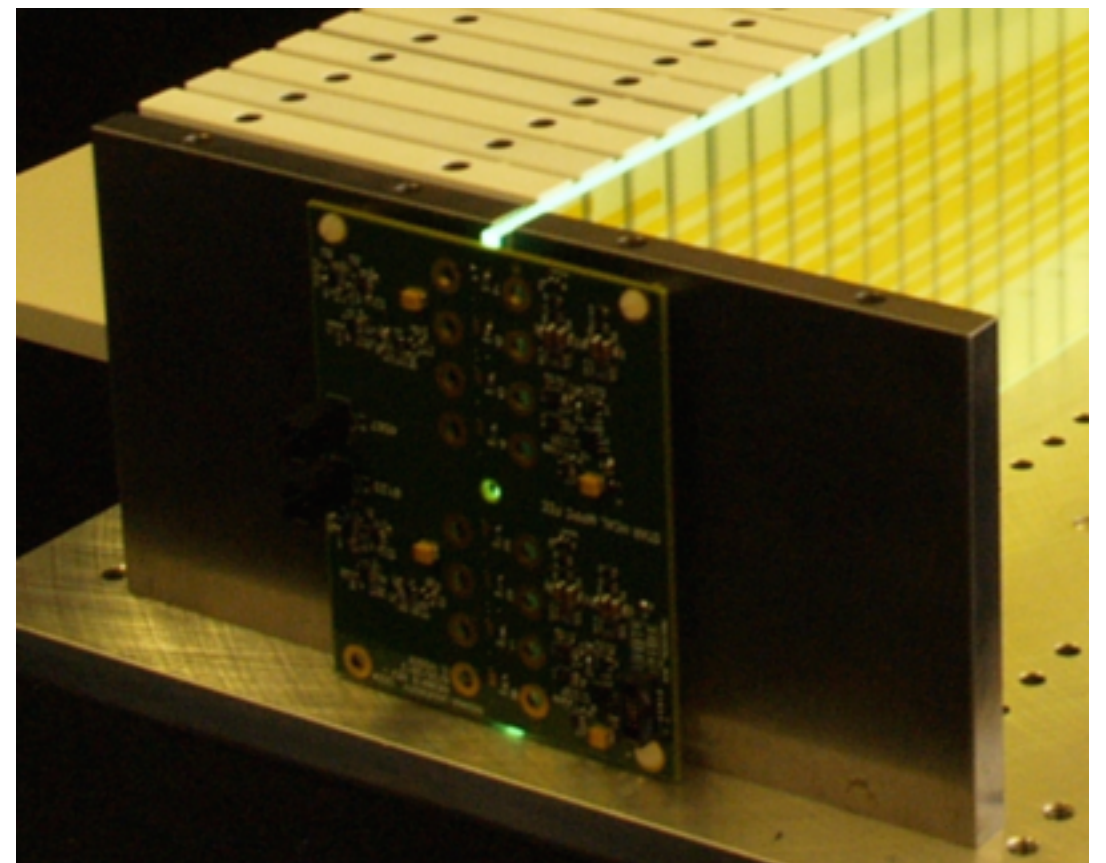
4-6 Si-strip disks, or pixels

8-10 GEM layers have been
considered as well

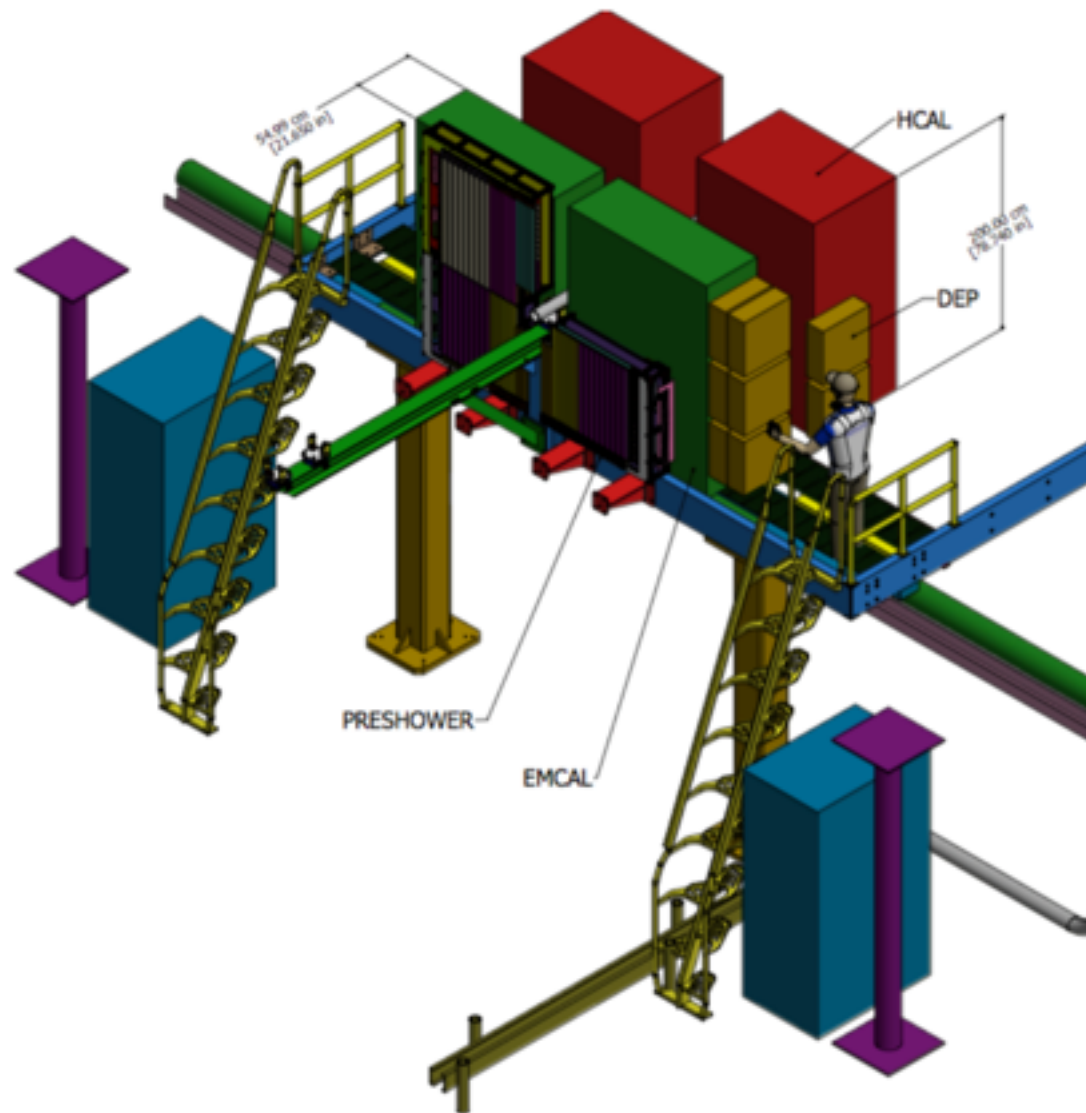
STAR FCS+FTS upgrade



was: W-powder EM-cal (sim.)
now: re-use PHENIX eCAL (cost)
new HCAL, based on
STAR/UCLA-EIC R&D



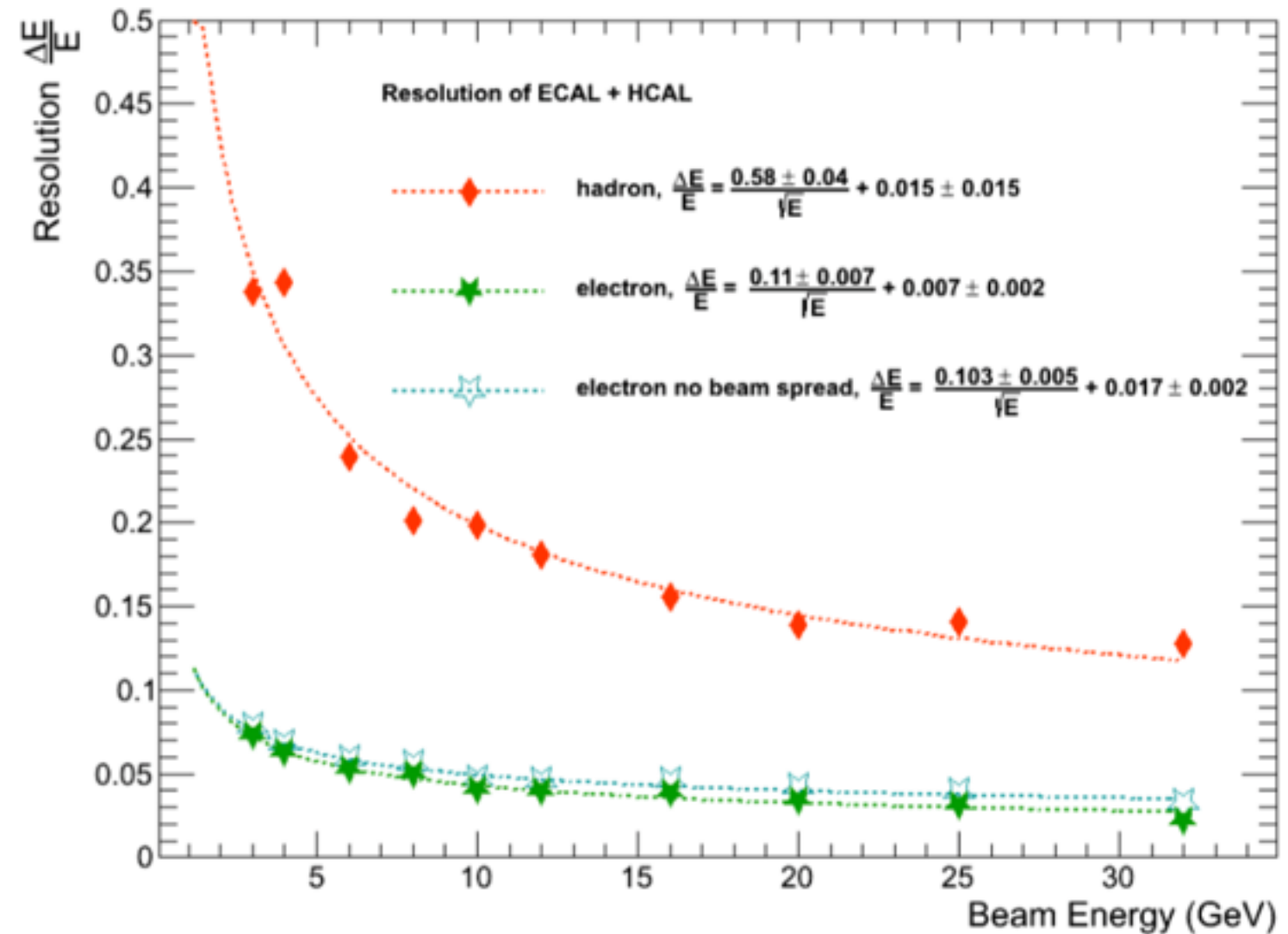
STAR FCS+FTS upgrade



was: W-powder EM-cal

now: re-use PHENIX eCAL

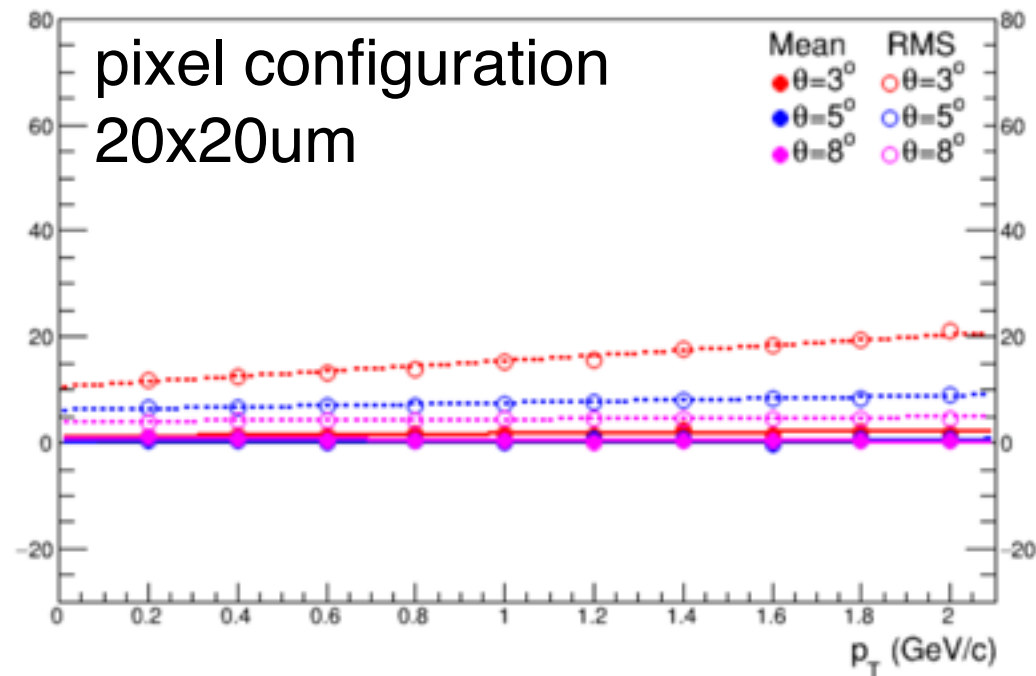
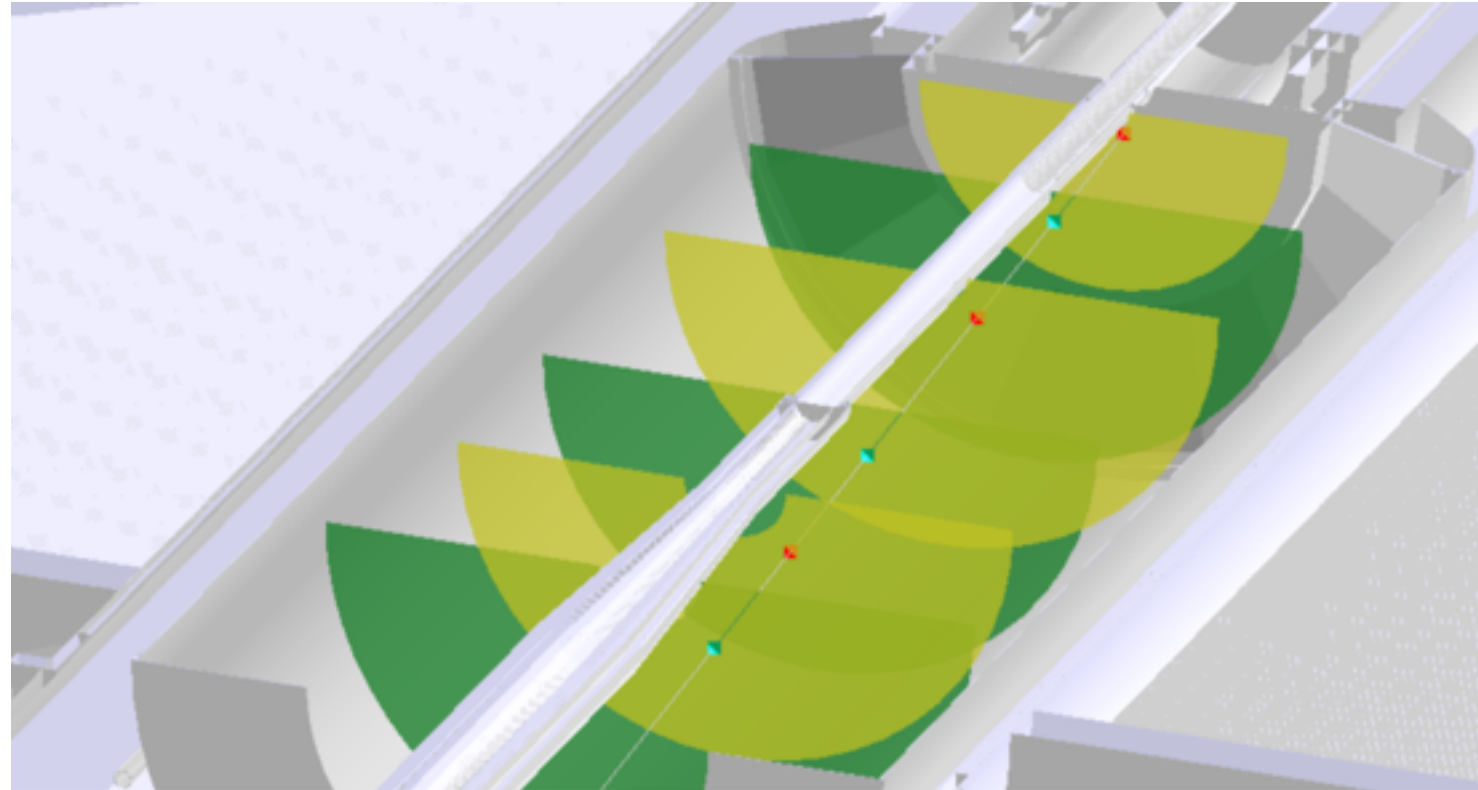
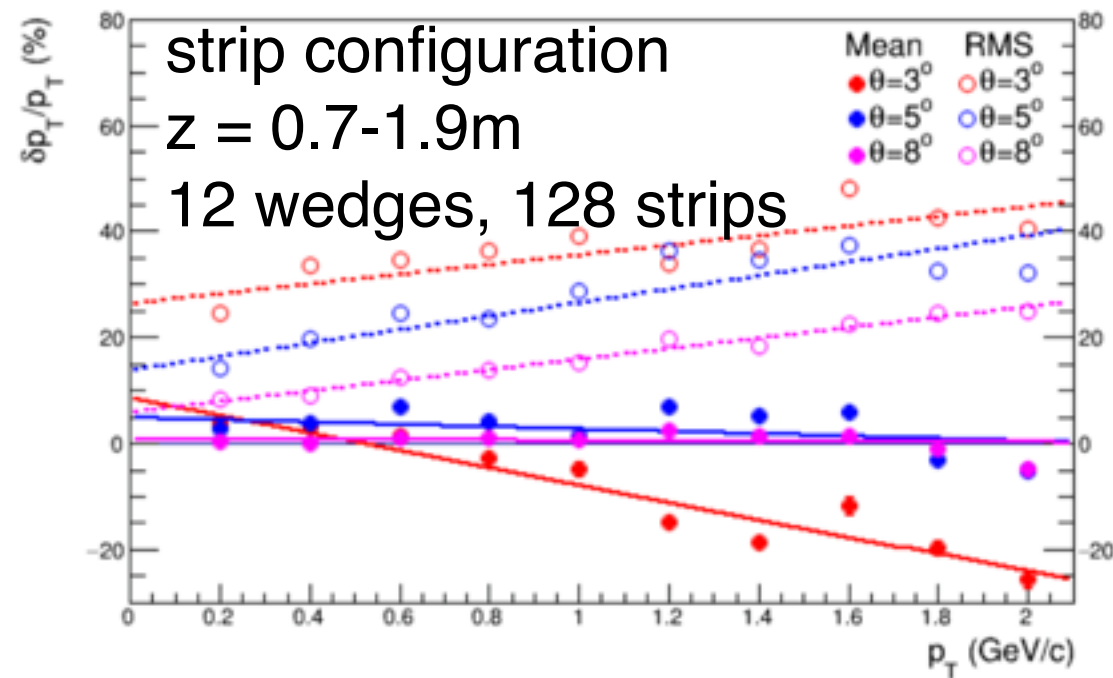
new HCAL, based on
STAR-EIC R&D



0.6M\$, incl. overhead and contingency

1.4M\$, incl. overhead and contingency

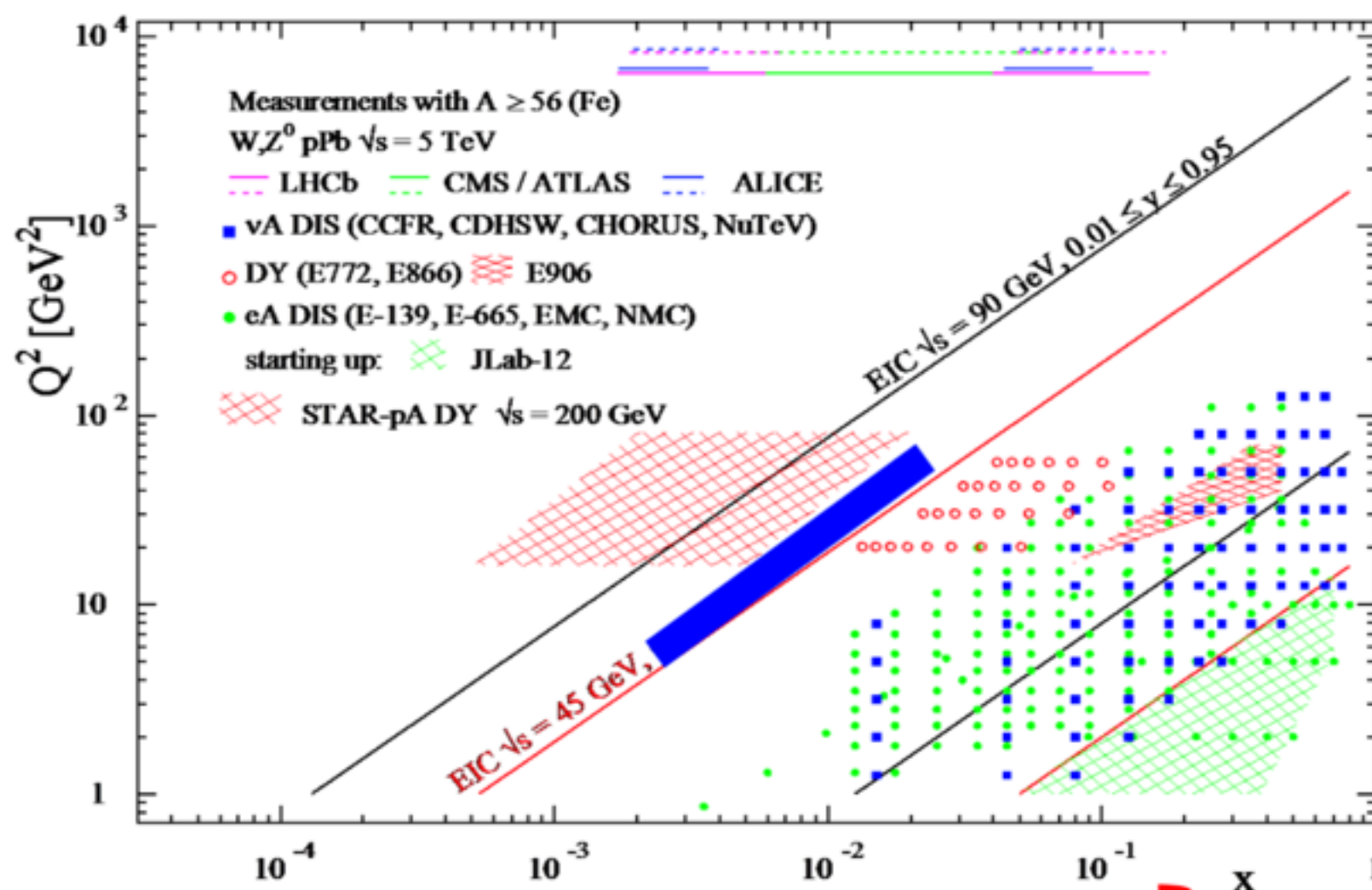
STAR FCS+FTS upgrade



3.8M\$, incl. contingency
overhead

4-6 Si-strip disks (sim.), or pixels,
8-12 GEM layers have been
considered as well,
existing mechanical support.

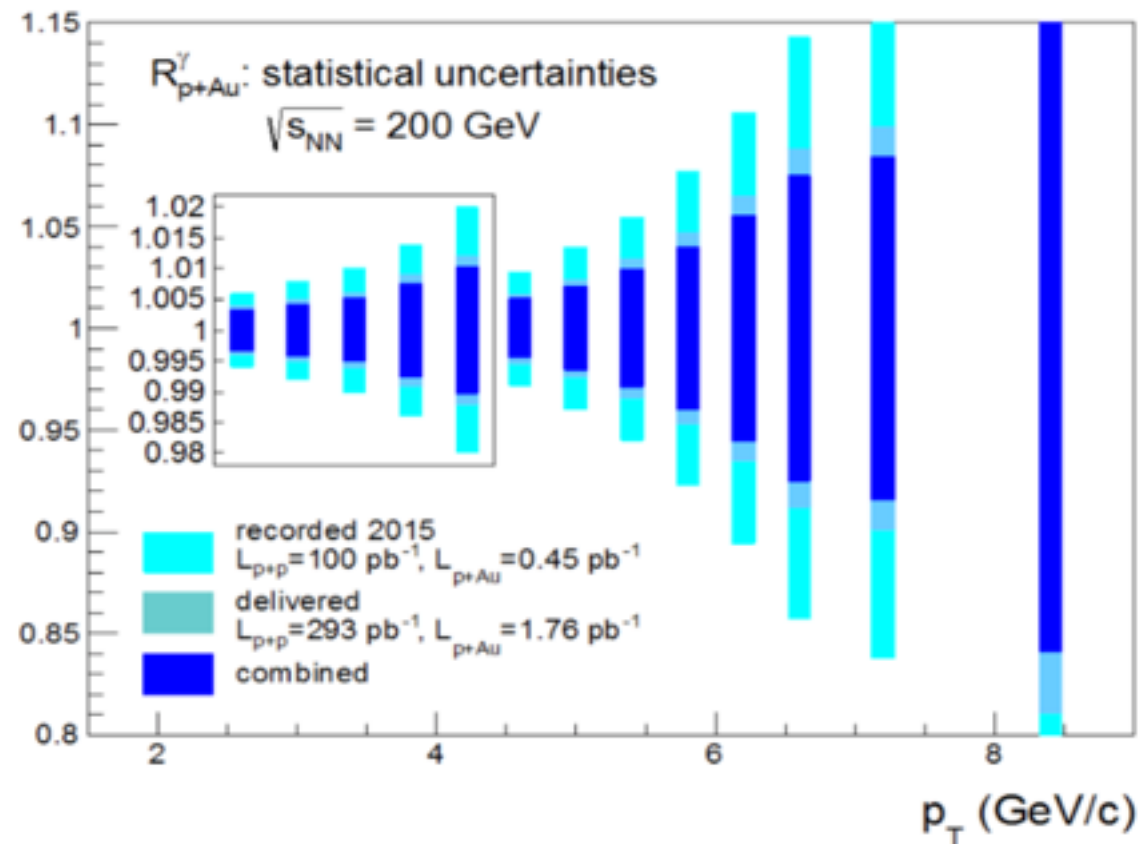
Key RHIC nPDF and saturation observables



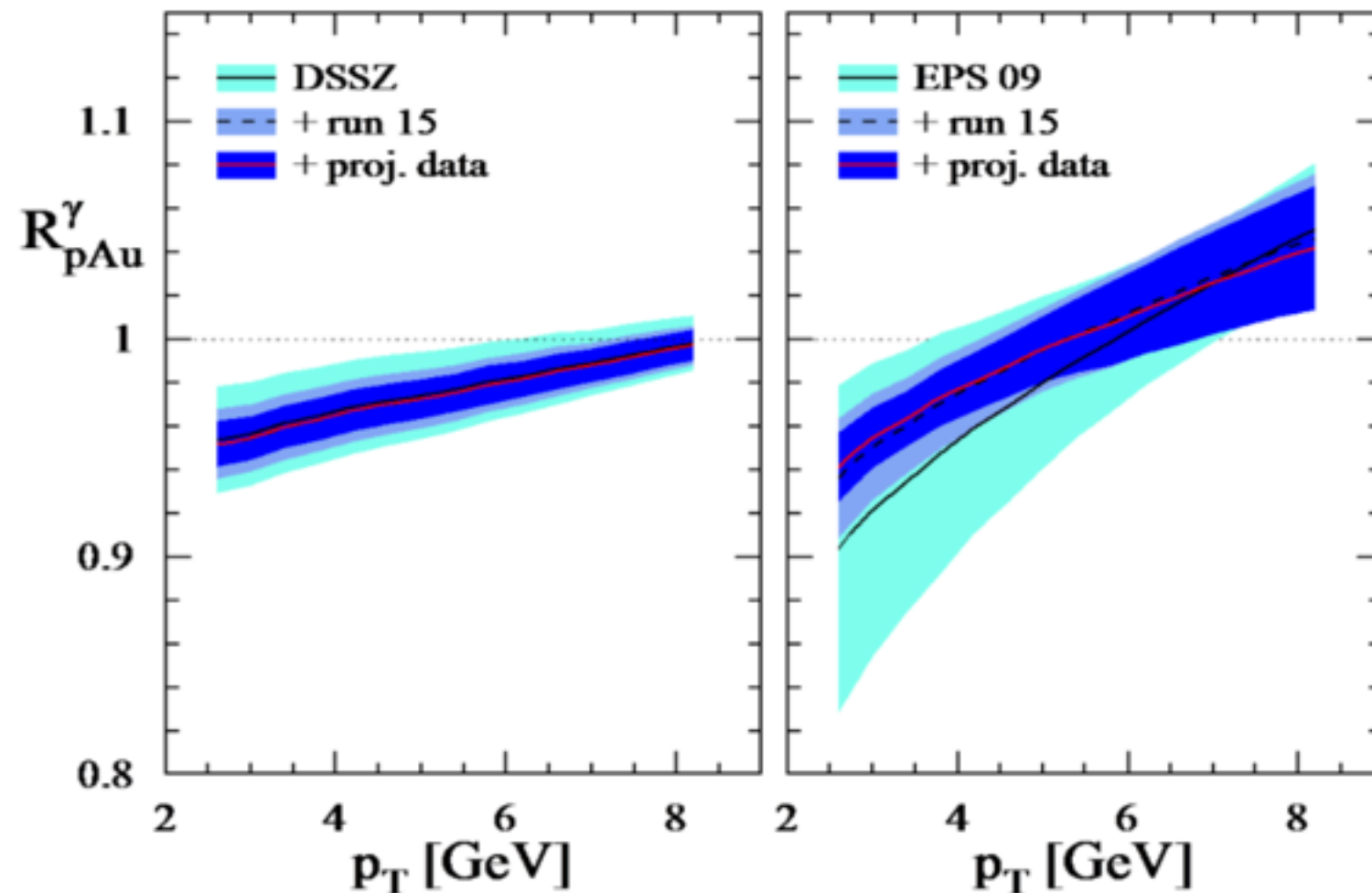
- Direct photon R_{pA}
 - R_{pA} for Drell-Yan (**needs forward upgrade**)
 - pA ultra-peripheral collisions: $g(x, Q^2, b)$
 - Di-hadron correlation measurements
 - $A_N^{pA}(\pi^0) / A_N^{pp}(\pi^0)$
 - Direct-photon + jet correlations (**needs forward upgrade**)
- No final-state effects!**

Direct photons

Data from p+Au run in 2015 and 2023

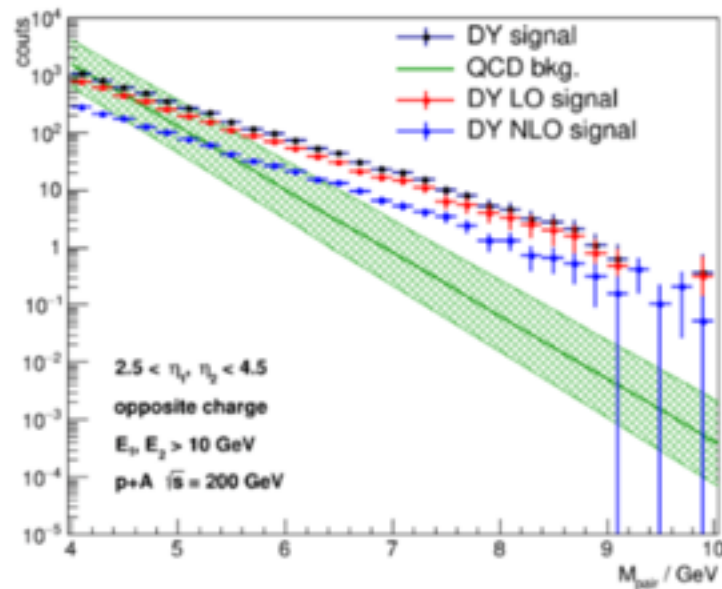


Projected impact on gluon nPDFs

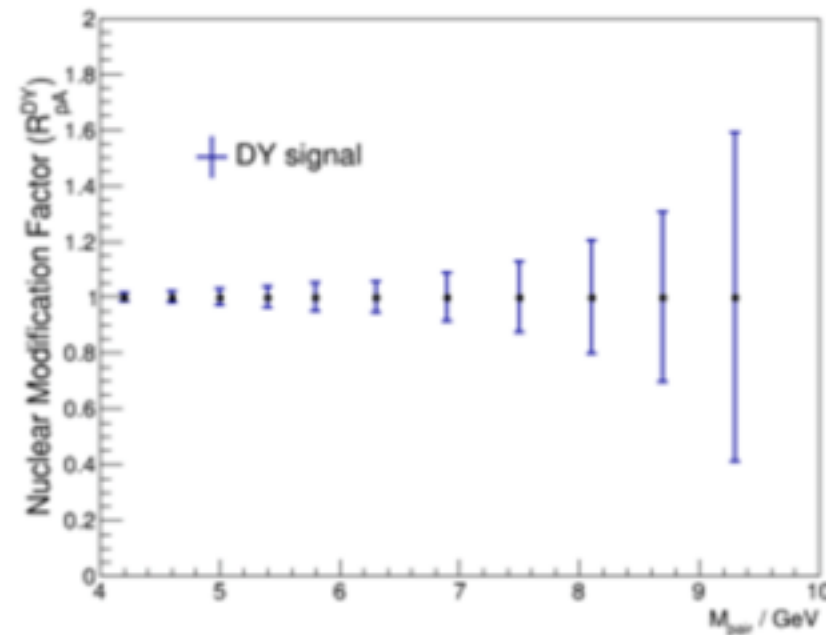


- Both direct photon and Drell Yan will provide:
 - Substantial improvements in our understanding of nuclear PDFs in the near term
 - Alternative observables and kinematics to EIC in the long term

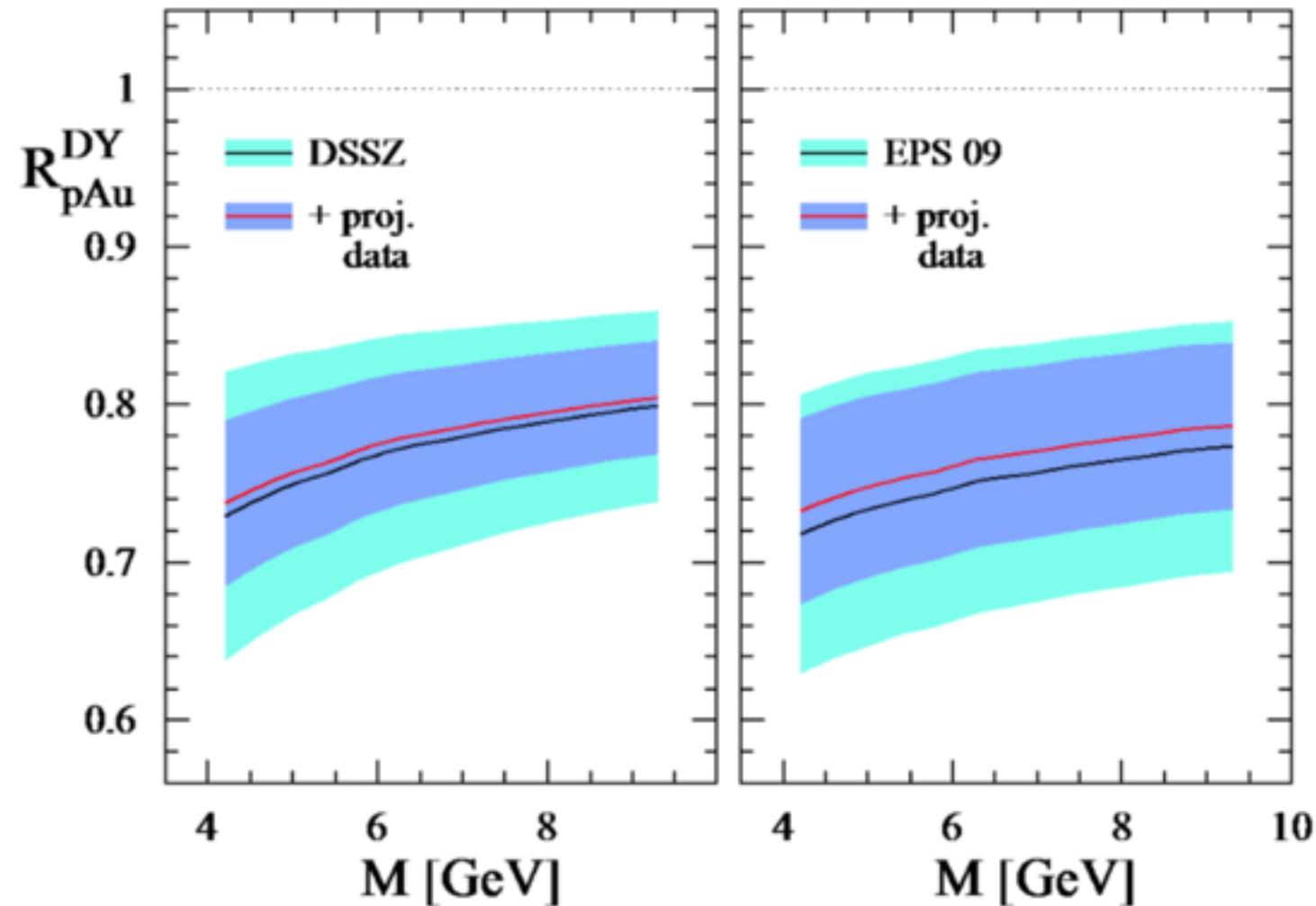
Drell-Yan R_{pA} at 200 GeV



Assumes
forward
upgrade

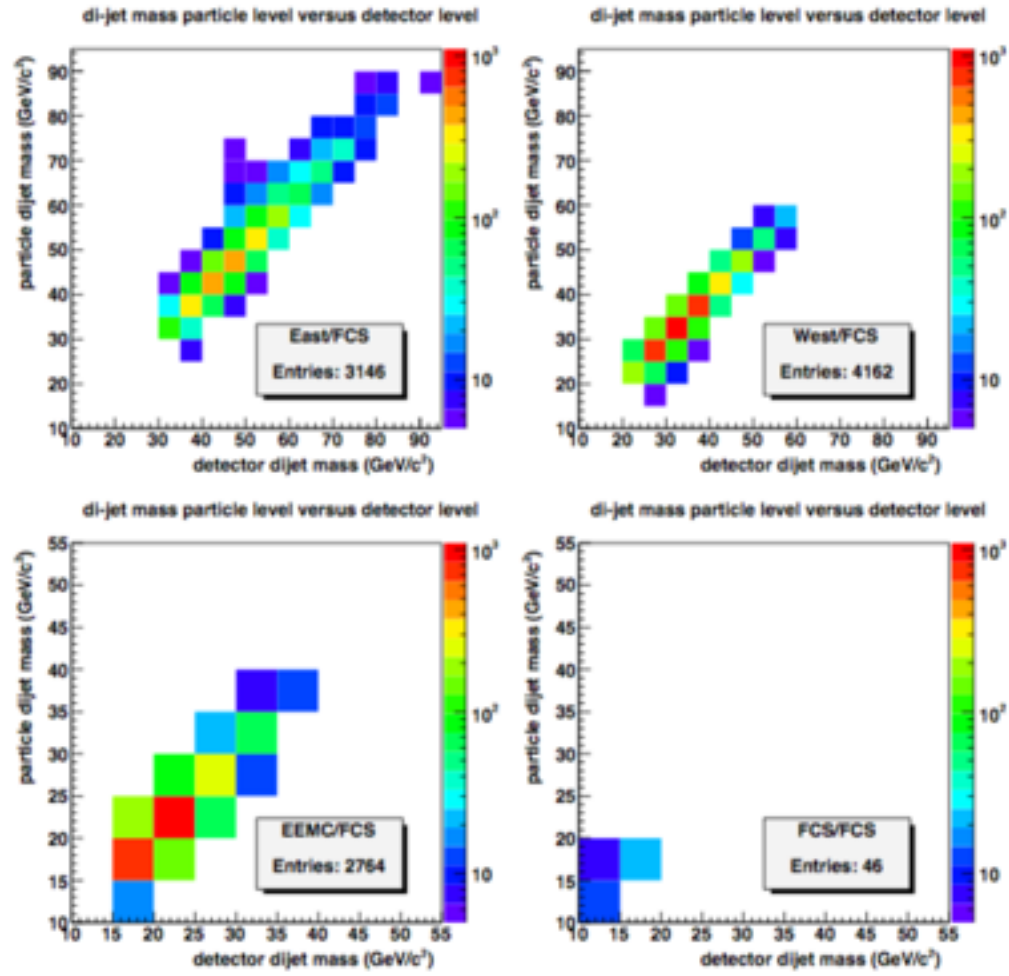


Projected impact on sea quark nPDFs



- Will obtain similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the low- x Q^2 lever arm relative to future EIC data

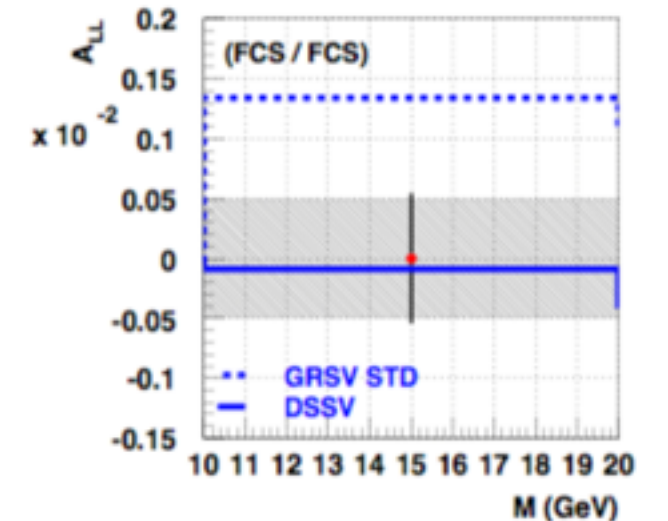
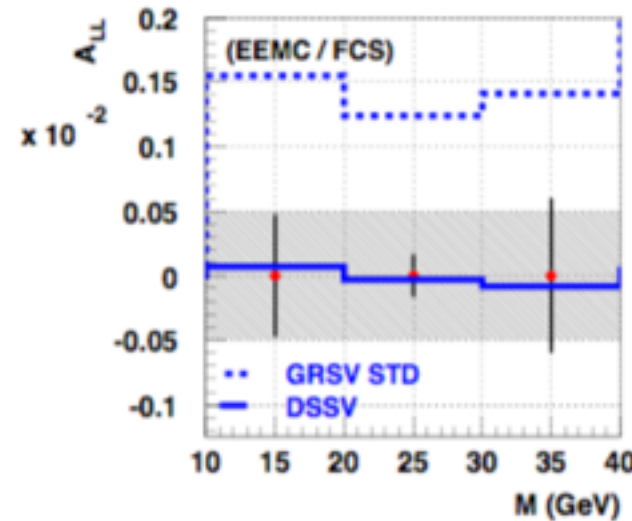
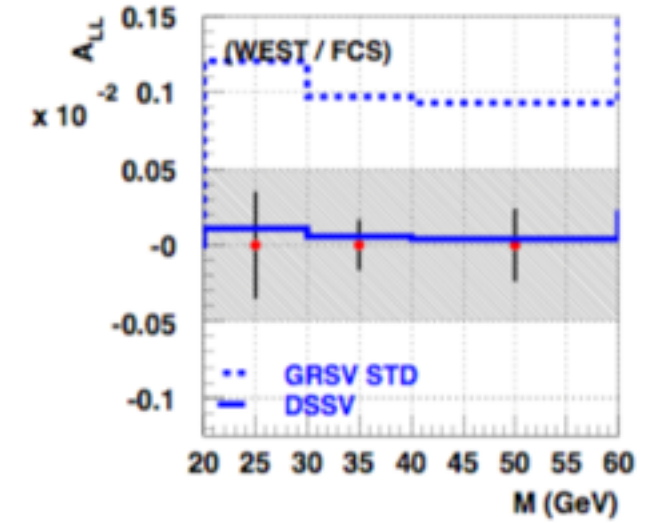
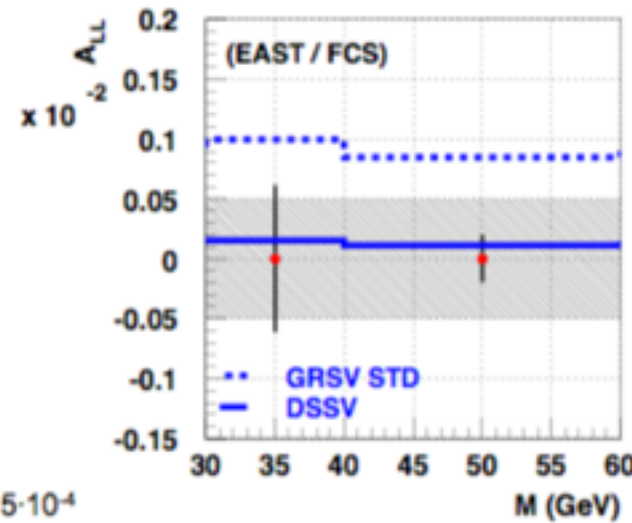
STAR simulated di-jets



$$\delta R = 5 \cdot 10^{-4}$$

$$\sqrt{s} = 500 \text{ GeV}$$

Delivered Luminosity = 1000 pb⁻¹
Polarization = 60%



Cone alg. ($R=0.7$) / $E_{T3} > 5 \text{ GeV}$ $E_{T4} > 8 \text{ GeV}$



Conclusion

	\sqrt{s} (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^\dagger p @ 510$ 400 pb ⁻¹ 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ , W^\pm , Z^0 , DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/ Ψ in UPC	A_N^{DY} : Postshower to FMS@STAR None None
	2023	$p^\dagger p @ 200$ 300 pb ⁻¹ 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. None None
	2023	$p^\dagger Au @ 200$ 1.8 pb ⁻¹ 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, nuclear FF Dihadrons, γ -jet, h-jet, diffraction	$R_{pAu}(DY)$: Yes Forward instrum. None Yes Forward instrum.
	2023	$p^\dagger Al @ 200$ 12.6 pb ⁻¹ 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl} : direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of h^\pm in jets, nuclear FF Dihadrons, γ -jet, h-jet, diffraction	$R_{pAl}(DY)$: Yes Forward instrum. None Yes Forward instrum.
Potential future running	202X	$p^\dagger p @ 510$ 1.1 fb ⁻¹ 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. None
	202X	$\vec{p} \vec{p} @ 510$ 1.1 fb ⁻¹ 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/ γ -jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program proposed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

A Few Closing Comments

If you believe that the report of the death of STAR after BES-II is *not* an exaggeration, then do keep in mind that the cold QCD program has/had the highest priority among the opportunities STAR outlined to the BNL-ALD and PAC past Fall,

The cold-QCD (spin) plan was requested directly by DOE-NP; it was submitted to the DOE in February, well *after* the BNL-ALD's decision to *not* support the STAR package of upgrades *at this time*,

A cost-race to the bottom is obviously not the goal, however, the guidance is/was about modest upgrades; both collaborations have become much more realistic in this respect since the pp/pA Lol,

Personally, I consider it unrealistic to assume that two forward upgrades will be realized at RHIC for 2020+; one or none seems much more realistic to me, how we choose to deal with this may matter,

The STAR and fsPHENIX concepts look increasingly alike, somewhat logical, but let me nevertheless ask, should we be worried about this?

Any delay w.r.t. sPHENIX cuts into the physics output in the current transition scenario,

Many thanks to many friends and colleagues for lots of discussions and work.